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EXPLORATORY DEVELOPMENT OF NONDESTRUCTIVE TESTING TECHNIQUES FOR DIFFUSION BONDED INTERFACES

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NORTH AMERICAN ROCKWELL CORPORATION

TECHNICAL REPORT AFML-TR-70-188

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FOREWORD

This document is the summary technical report prepared by the North American Rockwell Corporation Los Angeles Division, under Contract F33615-69 C-1397, for the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio. The work was administered by Dr. George Martin, Program Manager, under the direction of Mr. H.L. Stevens, MAMN, Project Engineer on Project No. 7351 "Metallic Materials" Task 735109 "Nondestructive Methods". The work described in this report has been carried out by Dr. George Martin, Mr. J.F. Moore, Mr. F.M. Coate, Mr. R.A. Brose, and Mr. J.A. Naughton. This program is coordinated with Contract AF33(615)-3515, Project 9122-1, "Fabrication and Evaluation of Diffusion Bonded Laminated Sections," under Mr. G.W. Trickett, MATP, AFML, and Mr. W.D. Padian, Program Manager, NR/LAD. The report covers the studies carried out in the period 1 February 1969 to 30 April 1970.

This report was submitted by the authors April 1970.

This technical report has been reviewed and is approved.

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ABSTRACT

The final technical report is presented for a program investigating nondestructive testing (NDT) methods for diffusion bonded aerospace structures. The NDT methods evaluation was performed on three prototype H-53 helicopter rotor hubs diffusion bonded from 1/2-inch titanium plate under a concurrent contract. The NDT evaluation included ultrasonic, radiographic, and penetrant methods, and showed that ultrasonic techniques offered significant potential for developing a reliable, high sensitivity inspection system. Conventional ultrasonic techniques were the primary NDT method evaluated, and significant progress is reported in applying ultrasonic techniques to complex diffusion bonded structures. A most important factor is the need for systematic evaluation and understanding of the material effects on the acoustic beam propagation characteristics. Detailed recommendations are made for ultrasonic test improvements including data recording and analysis techniques; a unique ultrasonic "nodding" transducer system for inspecting discontinuities not normal to the inspection surfaces; a servo-controlled transducer manipulator system; an automatically controlled recorder gate system; and an automatic digital signal depth and amplitude measuring system.

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SECTION I

INTRODUCTION

Solid-state diffusion bonding is proving successful in fabricating large prototype aerospace structures. As the demands for reliability in these structures are exacting, nondestructive test (NDT) methods capable of providing the required reliability assurance are essential.

Under Air Force Contract AF33-615-67C-1738, a preliminary survey was conducted of nondestructively processing diffusion bonded materials. It was concluded that conventional NDT methods are suitable for detecting discontinuities down to an area of about 1/32-inch diameter. High resolution ultrasonic techniques adapted under this contract allowed depth location of such discontinuities to within a few thousandths of an inch. In addition, methods based mainly on shear wave velocity and longitudinal wave attenuation measurements were developed which indicate that direct relationships may exist between these measurements and the actual strength of the diffusion bond. It was further concluded that metallurgical knowledge of the nature of the bond interface and its relation to mechanical properties was inadequate for comprehensive defect-to-property correlations.

This report describes the continuation of these efforts, directed at the most expeditious integration of this development into test systems for actual structures. The diffusion bonded structures presently of major interest to the Air Force comprise relatively heavy sections. This program, therefore, aimed mainly at the problems associated with inspecting relatively heavy sections. However, it is appreciated that other families of structures are also being considered by the Air Force, such as structures bonded together from very thin sheets forming facing sheets and stiffeners. Such materials present a number of special nondestructive inspection problems.

The contractor is also presently engaged in a program for the experimental fabrication of the H-53 helicopter rotor hubs by diffusion bonding (AF33(615)-3515). Three rotor hubs fabricated under this program were utilized as test specimens for NDT, metallurgical, and mechanical property correlations. Further, the NDT results have been used to design a complete nondestructive inspection system and procedure for the rotor hubs.

SECTION II

SUMMARY

This report describes an investigation for nondestructive methods for testing large and complex diffusion bonded structures. Three H-53 helicopter rotor hubs, fabricated by diffusion bonding processes, were nondestructively evaluated using ultrasonic, penetrant, radiographic, and visual test methods. The nondestructive test (NDT) results showed no significant discontinuities that could affect the performance of the rotor hubs in service. The NDT results were correlated with metallurgical examinations and mechanical property tests. The metallurgical examinations confirmed that the ultrasonic test sensitivity was sufficient to detect minor grain structure variations equivalent to the response from a 3/64-inch flat bottom hole standard in rotor hub metal travel distance of 7 inches. In addition, the tensile and fatigue properties of rotor hub specimens including the 1/2-inch laminate interface and scarf joint interfaces showed no discontinuities, and strength levels approximated the properties of the plate stock material. Ultrasonics was the primary nondestructive test method evaluated and significant progress is reported in the utilization of ultrasonic techniques for complex diffusion bonded structures. The most important factor gained from the ultrasonic studies is the need for systematic evaluation and understanding of the material effects on the acoustic beam propagation characteristics. The rotor hub exemplifies a wide range of shape and material variations that can be misjudged, and that either independently or in combination - can invalidate the test investigations. These variations are discussed in general terms and apply to most complex structures. Detailed descriptions of these variables in terms of the specific rotor hub components and test considerations are included. This information in conjunction with the recommended calibration standards and procedures should enable a qualified ultrasonic inspector to perform a competent evaluation of a rotor hub.

The applicability of penetrant and other visual type techniques for surface emergent discontinuities was established and should be employed with ultrasonic techniques for a complete nondestructive rotor hub evaluation. The radiographic evaluation confirmed the applicability of the method for detecting gross differences in material densities such as tungsten inclusions in titanium sections, but negligible applicability for air or gas type discontinuities. Radiographic techniques did show an unanticipated applicability for the detection of the yttrium oxide stopoff material used for deliberate disbond standards. In this regard, radiographic techniques could be used to cross check the ultrasonic detection and location of deliberately introduced disbond standards in areas of the rotor hub that subsequently are removed during machining.

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The use of conventional ultrasonic test systems for complex structures such as the rotor hub has limitations, and certain improvements are recommended. It should be noted that these limitations are not generally attributable to current equipment designs but to the more extensive requirements of large complex structures. Detailed recommendations for specific system improvements are reported, including improved NDT data recording and analysis techniques; a unique ultrasonic "nodding" transducer system for inspecting diffusion bonded areas where discontinuities are not normal to the inspection surface; a servo-controlled transducer manipulator system for automatic compensation for changing water path; an automatically controlled recorder gate width and location system; and an automatic digital signal depth and amplitude measuring system.

Recommendations are made for future studies directed toward the NDT characterization of a range of types and sizes of discontinuities using a series of specially designed diffusion bonded specimens. Such a program should be directed toward not only evaluating and developing NDT methods but also include a correlation with a range of mechanical properties selected for specific stress and load rate conditions. This approach will lead to the definition of realistic diffusion bonding acceptance criteria.

Section III

NONDESTRUCTIVE TEST DEVELOPMENT

TECHNICAL OBJECTIVE

This study evolved from the preliminary investigation into nondestructive tests for diffusion bonded materials reported in reference 1. That investigation assessed the current state-of-the-art and evaluated potential nondestructive methods for testing diffusion bonds. Although no nondestructive test (NDT) method had been established to measure diffusion bond strength, it was concluded that a correlation exists between ultrasonic attenuation and velocity, and the tensile strength in diffusion bonds.

Test results also showed that existing ultrasonic and radiographic test methods can detect and define discontinuities at the diffusion bonded interface or within the laminate material. In particular, ultrasonic methods proved uniquely successful in locating very small imperfections in both relatively thick (3-inch) and rather thin (0.64-inch) bonded laminates, and dye penetrant methods were successful in detecting surface emergent discontinuities. Limited inspection capabilities were exhibited by eddy current and infrared methods to locate either surface or near-surface defects, and vibration-damping methods were successful for inspecting only thin materials.

In the present program, the objective has been to further establish the ability of NDT methods to indicate material properties as well as discontinuities in complex configurations that have been diffusion bonded. The specific goal was to design and characterize an inspection system for the H-53 helicopter rotor hub.

The NDT system designed for a complex rotor hub structure must satisfy several requirements:

1. It must be able to inspect the heavy rotor hub in situ. That does not necessarily mean a portable system, but the design must permit the system to be installed in a manufacturing area.

2. Operating procedures and data presentation must be standardized to permit semiskilled personnel to perform the inspection with a reasonable degree of assurance.

3. The test system must be able to indicate major discontinuities or unbonded areas with reasonable speed.

4. Test standards and the resolving power of the NDT system must provide the data that allow the properties of doubtful areas to be arbitrated.

5. The system should be able to inspect critical areas in the part for which it is designed, regardless of the part's geometry.

Eventually, it also is desirable to make the system adaptable to being incorporated into an automatic scan-record and analysis system.

SPECIMEN DESCRIPTION

A number of diffusion bonded specimens were provided for this program by the Air Force Materials Laboratory.

Under Contract AF33(615)-3515 (reference 2), three experimental helicopter rotor hubs were diffusion bonded in the configuration shown in figure 1. Each rotor hub weighs approximately 400 pounds as bonded and is 54 inches in overall diameter. The three basic laminate types in the hub are shown in figure 2. The lower center section consists of concentric ring laminates with a uniform inner diameter and three outer diameters. The extended center laminates form the arms and part of the lugs. The lugs are completed with concentric ring laminates of fixed inner and outer diameters. Laminates are machined from 1/2-inch Ti-6Al-4V alloy plate and are joined by 60-degree scarf joints, as shown in figure 3.

MECHANICAL PROPERTIES

Mechanical property tests determined tensile and fatigue properties reported in reference 2. Comparison of smooth, round-bar tensile specimens from various locations in the rotor hub arms and center section showed uniform tensile properties with respect to specimen location and orientation. Although tensile test results comparing as-received plate and the bonded laminates showed slightly lower tensile strength for the laminate, they were well above the minimum rotor hub design requirements for yield (120 ksi) and ultimate tensile strength (130 ksi).

Smooth, round-bar fatigue test specimens of bond lines in the reduced cross sections were tested. Specimens were oriented both longitudinally and transversely in relation to the plate rolling direction. Fatigue tests revealed no abnormally short-life specimens. Neither were there any anomalies to indicate bond line failures noted on the fracture surfaces. Unnotched fatigue property data for the rotor hub fell within the data scatter and were in agreement with similar data on the first rotor hub.

A vertical section, 4.5 inches wide by 6.5 inches long and 1.5 inches thick, which contained a number of the 60-degree scarf joints, was removed from the upper center section of the second rotor hub. After this slab was

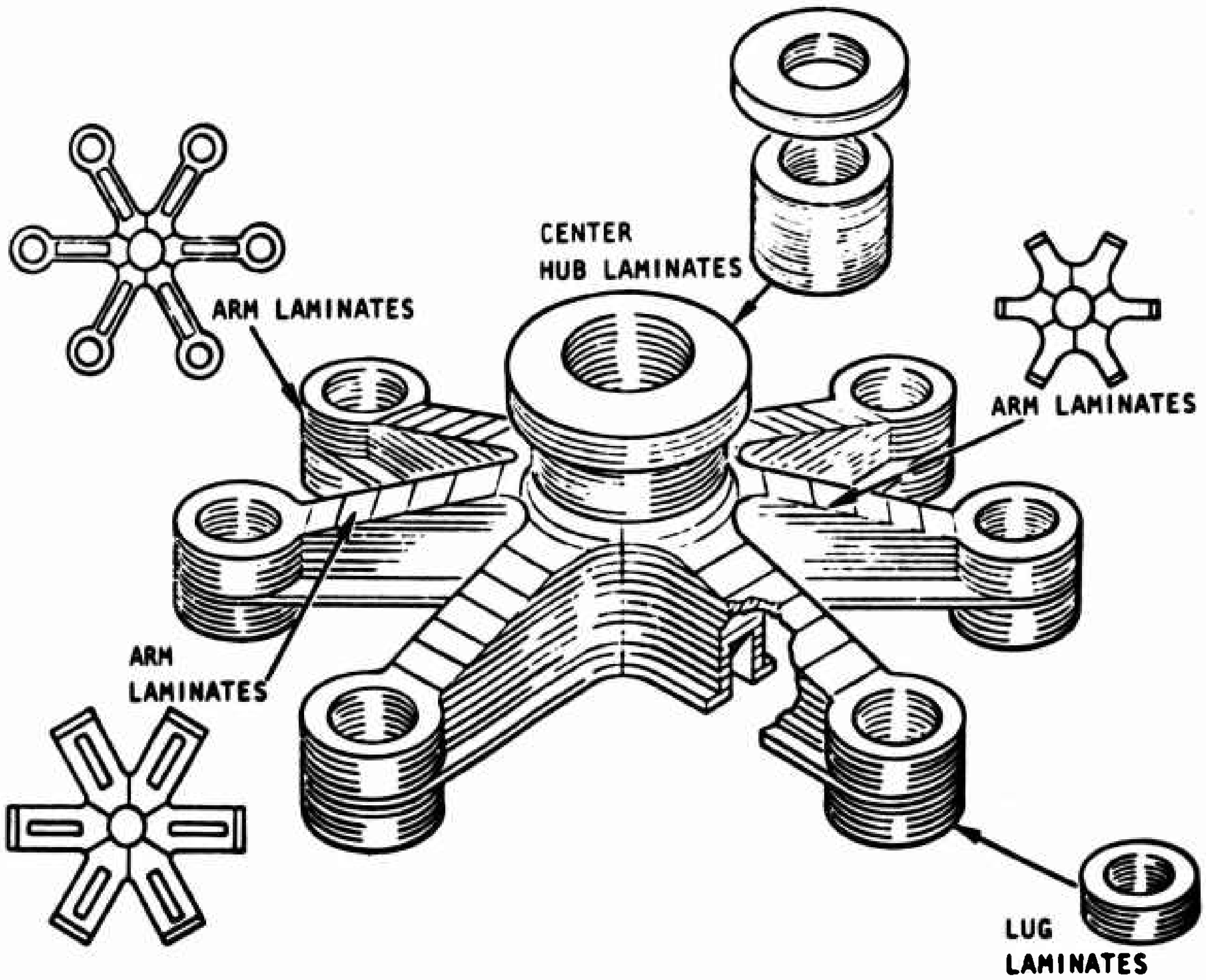


Figure 1. Diffusion Bonded H-53 Rotor Hub

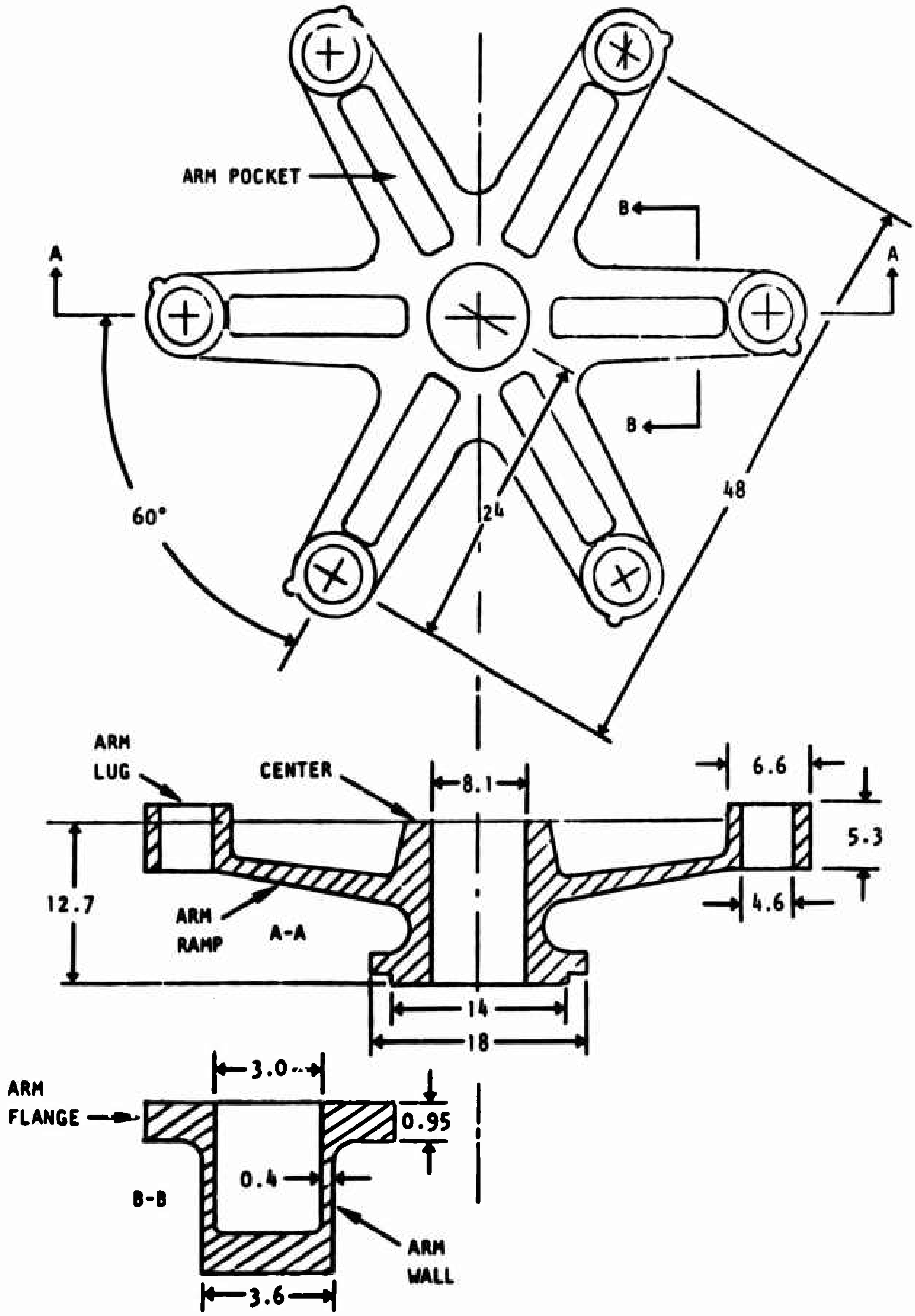


Figure 2. Rotor Hub Dimensions and Section Nomenclature

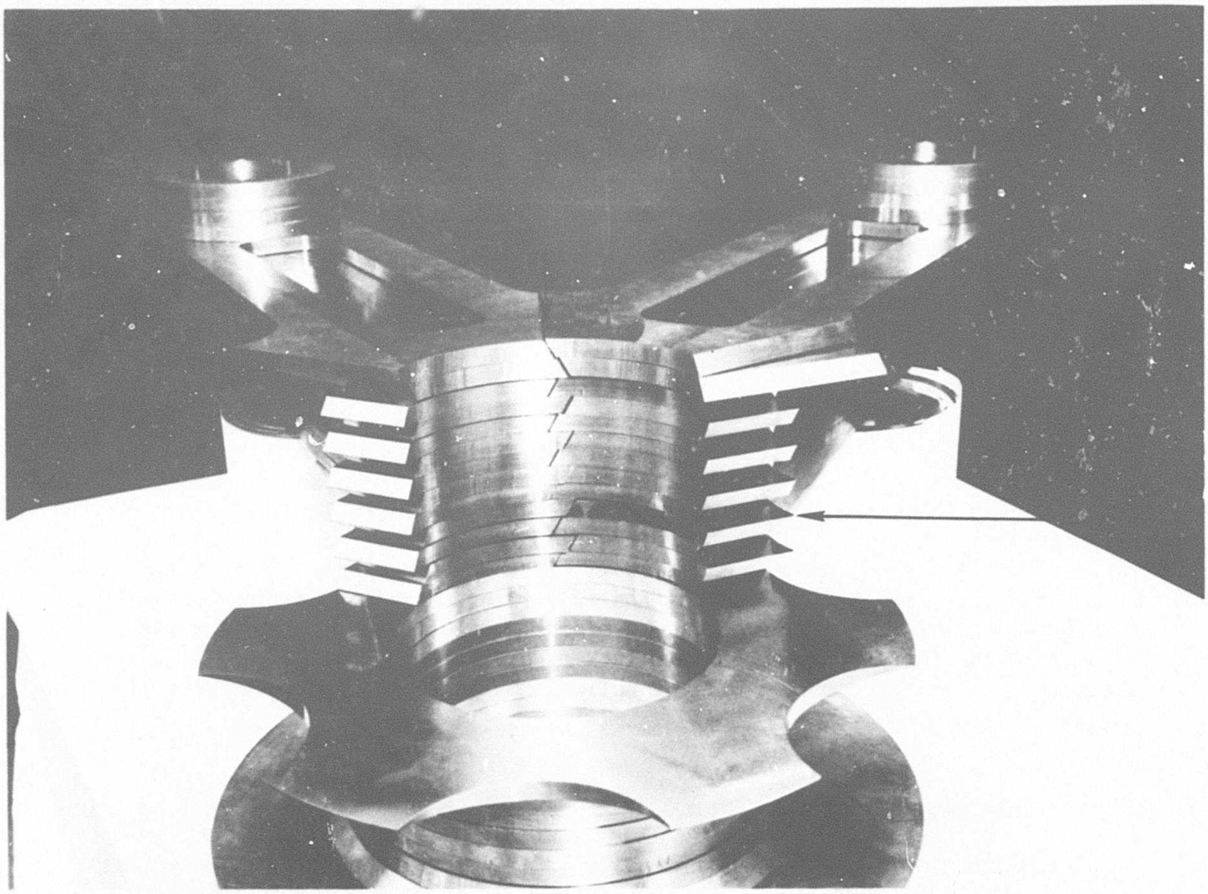


Figure 3. Photograph of Rotor Hub Laminates Showing Scarf Joint Details

macroetched to reveal the exact locations of the scarf joints, smooth bar fatigue specimens with a joint at the midpoint of each specimen were carefully machined from the slab. Specimens were approximately longitudinal in orientation to the rolling direction of the original plate material. Test results agreed well with fatigue data for other hub sections and no bond line failures were observed in the fractured surfaces of any specimens.

Circumferentially notched (K_t = 3.0) fatigue specimens from various locations in the second rotor hub were tested at maximum stress levels of 35 to 50 ksi. Notched fatigue properties were uniform throughout, and were not affected by specimen orientation.

METALLOGRAPHIC PROPERTIES

Metal Flow

Macrosections of representative rotor hub areas were obtained to determine the magnitude of metal flow that affects orientation of the plane at the original bond interface. Figure 4 illustrates the considerable metal flow in the narrow arm sides and appreciably less flow in the center and lug sections. Nondestructive inspection methods for detecting bond line phenomena must consider bond line orientations at continually varying angles other than parallel to the relatively flat top and bottom surfaces. Insufficient metal flow was evident in the third rotor hub due to lack of die fill in the arm walls. This condition, which was apparent without optical magnification, was attributed to an interrupted bond cycle.

Surface Characteristics

As-bonded surface roughness nominally is 125 microinches RMS, with typical measured variation from 100 to 275 microinches; it is attributed to tooling surface finish and oxidation. Metallographic examination of selected areas showed that interaction had occurred between the titanium and the ACI HH (Type II) tooling during bonding, an interaction previously recognized in bonding studies. The surface diffusion zones that resulted, shown in figure 5, ranged from approximately 0.002 inch to 0.008 inch deep in local areas. Although contaminated surface material is removed during rotor hub machining, these zones significantly scatter and attenuate ultrasonic energy during inspection of the as-bonded hub.

ULTRASONIC TEST METHODS

Ultrasonic inspection techniques have proved to be the most promising means of detecting material and interface discontinuities in diffusion-bonded

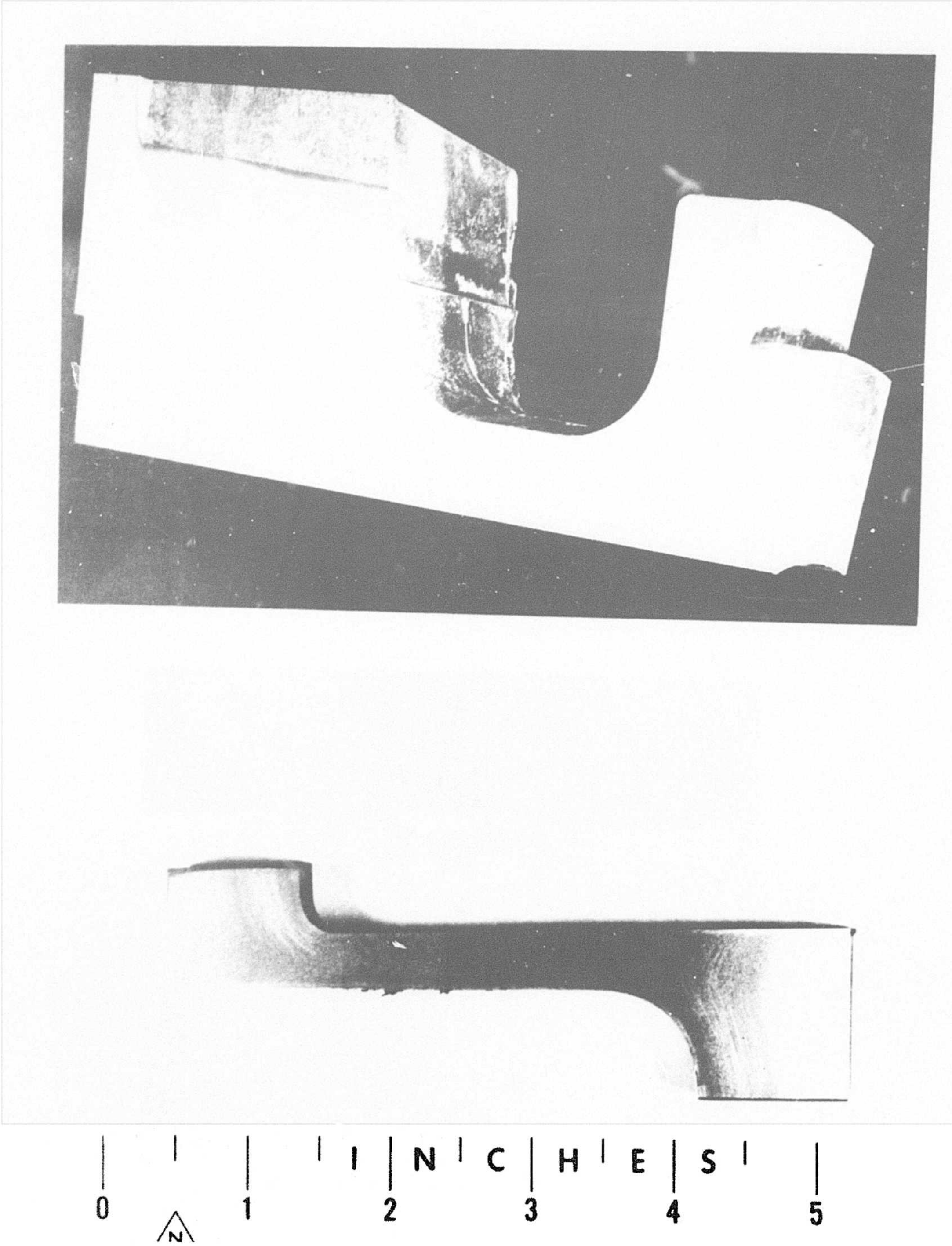
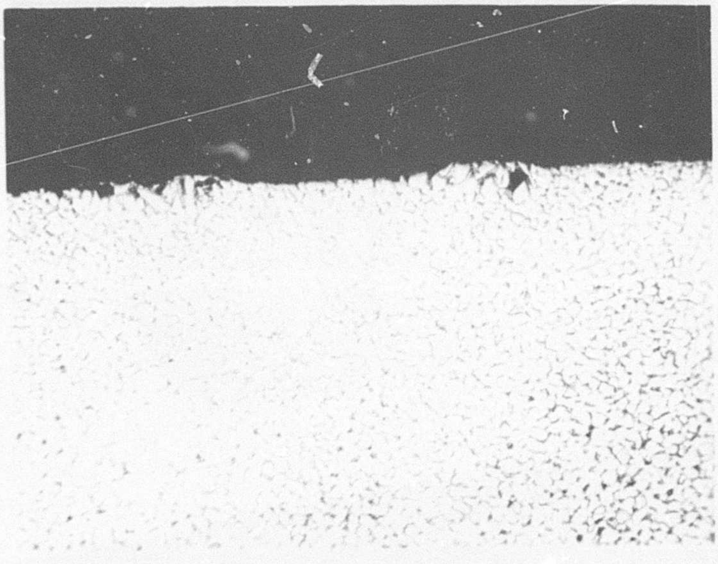
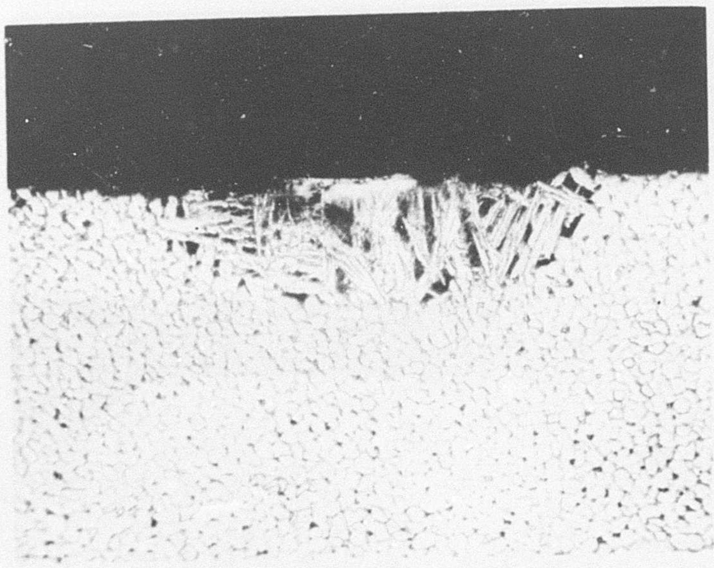


Figure 4. Photographs of Rotor Hub Sections Etched to Show Metal Flow



TYPICAL TITANIUM - TOOL INTERACTION (100X)



SPOTTY TITANIUM - TOOL INTERACTION (100X)

Figure 5. Titanium-Tool Interaction

laminates (reference 1). NR/LAD quality assurance specifications for the ultrasonic inspection of diffusion-bonded parts (reference 3) are based on variously shaped materials. Complex-shaped diffusion bonded structures such as the rotor hub present several unique inspection conditions: Metal thicknesses up to 12.5 inches are encountered, bonded fillet radii are varied, and there is a significant lack of parallelism between bonded interfaces and the normal inspection surfaces because of metal flow and the angle joints between laminates in the same material layer. Therefore, ultrasonic evaluations were made on three rotor hubs to (1) establish the capabilities of conventional, commercially available ultrasonic inspection systems and techniques, (2) determine technique or equipment development requirements, (3) establish ultrasonic inspection standards and procedures, (4) develop suitable rotor hub support and positioning fixtures, and (5) characterize the ultrasonic test response through material property tests and destructive examinations.

Ultrasonic inspection test sensitivity is affected by a number of test system variables and material characteristics. The ultrasonic instrument has many components that help to control system overall sensitivity. The amplitude and shape of the transmitter drive pulse are fundamental factors in determining ultrasonic signal strength. Gain of the receiver is the most obvious influence on sensitivity, but frequency response determines not only the amplitude but also the frequency components that will be used for the measurement. This can change the penetration and the effective shape of the beam, and thus the ratio of sensitivity between areas near the surface or deep within the part.

Measuring system sensitivity is strongly affected by transducer characteristics. Piezoelectric materials have different efficiencies. Beam size and shape control energy concentration within the test area.

Attenuation within the material will change the signal amplitude directly. Another factor closely associated with attenuation is background or metal noise, which tends to obscure or mask small signals that represent specific irregularities. When the system gain is reduced to lower the noise level, the signals are also reduced.

Many variables in sensitivity can be eliminated by using a good reference or comparison standard. For example, the transducer, transmit pulse, and receiver are the same for the test part and the reference block. Variations in these factors are compensated by comparative readings when the system is alternated between the standard and the test part. Attenuation in bulk material normally is not the same for the reference standard and the part. Once this value has been established, however, the difference can be compensated. Variations in attenuation due to surface condition are more difficult to evaluate. Two areas an inch apart may display very different characteristics.

MEASUREMENT SYSTEM

The basic ultrasonic test system employed in the evaluation consisted of the latest commercially available flaw detection instruments, an automatic scanning-recording system, and associated transducer manipulator and controls (figure 6).

Pulser-Receiver System

The following ultrasonic instruments were used:

1. Automation Industries Immerscope Model 725 Type D, Style 50A000900, S/N 1855-9 with a Pulser, Type 725-R1, and a Flaw Gate, Type FG1

2. Electrocircuits Immerscope Model 424 S/N 53

3. Sperry Reflectoscope, Type UW, Style 50R025 SN 61017

4. Erdman Model 1177 Hires Pulser-Receiver as modified by NR for precision velocity measurements

The majority of the ultrasonic C-scan testing and material property measurements were performed with the Model 725D Immerscope. The other instruments are similar but have somewhat different characteristics.

The excitation drive pulse is in the form of a sharp pulse caused by a voltage step. Some instruments use a short burst of RF energy, which usually delivers more power but gives poorer resolution. Amplitude of the Immerscope 725D transmitted pulse was measured at about 750 volts. Pulse frequency can be selected in steps from 50 to 5,000 pulses per second.

The receiver will handle a wide dynamic range of input signals, and, since safe limiting is provided, the circuits recover quickly after high overloads. Full-scale output requires only a few millivolts at maximum gain, yet the transmit pulse will not damage the input. Broadband tuning is provided at frequencies from 1 MHz to 25 MHz.

Receiver output is available through external terminals and presented visually as a cathode-ray tube (CRT) display. Horizontal sweep is synchronized with the transmit pulse. The sweep can be delayed and expanded to examine any response in detail. Sweep speed can be selected to establish an integral relationship between the horizontal scale and inches of travel through the common materials.

Most ultrasonic test systems provide depth information in the form of pulse-echo signals as spikes displayed on a calibrated time base of the CRT. Depth reading accuracy depends on the accuracy and linearity of the sweep circuit and on operator skill in subdividing the horizontal scale.

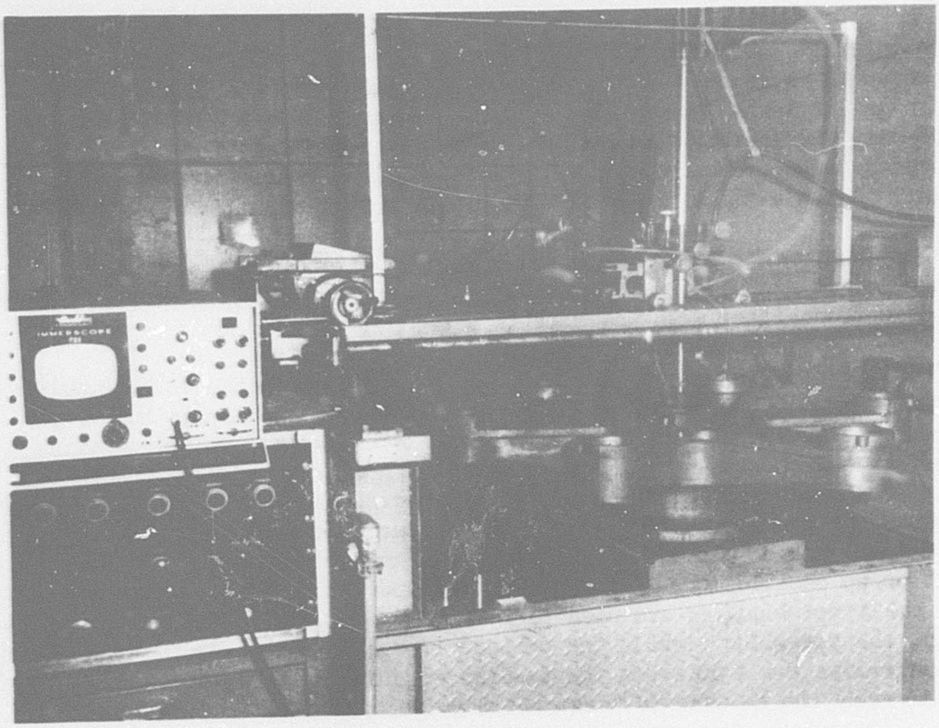


Figure 6. Ultrasonic Test System and Scanner-Recorder System

With a digital timing system that was developed, depth measurements were obtained more accurately and quickly than can be read directly from the CRT screen. Figure 7 shows the front panel of the depth gage and its power supply unit. The digital readout is normally made from the four Nixie lamps in the rectangular windows.

An internal, 10 MHz, crystal-controlled time base allows the timing pulses to be moved in increments of 0.1 microsecond, and measurements can be interpolated to as little as 20 nanoseconds. An external frequency source can be used to vary the increments from 0.08 microsecond or less to greater than 1.0 microsecond. The frequency can be adjusted to display readouts in inches of material. As an example, each count might be 0.01 inch.

This instrument can initiate the transmit pulse and start the timing sequence, or it can be slaved to initiate from a sync signal generated by the ultrasonic transmitter with which it is being used.

The time base signal enters a four-decade counting circuit where pulses are counted from 0000 to 9999 or until another transmit pulse is initiated. Each of two coincidence circuits, identified as channels A and B, contains four rotary switches allowing selection of any number up to 9999. When the counter reaches the preset value, a narrow rectangular pulse (50 nanoseconds) is produced at the appropriate output jack. Both the A and B pulses reach a third output jack on one line. These three outputs can synchronize a gate circuit or an oscilloscope sweep, or can be superimposed on the video signal. And if the A and B pulses are used to initiate the sweep just prior to the video signals, the two video signals can be superimposed. Likewise, the A switches can superimpose the A pulse on the leading edge of the first video pulse, and the B switches can be used to place the B pulse on the leading edge of the second video pulse. The time, or distance, between the two ultrasonic echoes can be measured by subtracting time A from time B. Channel B in figure 7 is set to 1456 increments of 0.1 microsecond giving a time of 145.6 microseconds. Channel A, set to 22.2 microseconds, produces a difference of 123.4 microseconds.

The Nixie indicators and their associated decade counters can be used in two ways. They can be made to start counting at the A pulse and stop counting at the B pulse. This automatically measures the time from A to B or subtracts the A count from the B count, as shown. When using the second type of operation, the A pulse only unlocks or enables the start channel, and the next video signal will start the count. The B pulse unlocks or enables the stop channel so the next video signal will stop the count. In this mode of operation, the A and B pulses are set to occur somewhat before the desired echoes, and the video signals perform the start and stop function. The Nixie readout tracks the video, and readings change as the echoes change spacing from one part of the specimen to another.

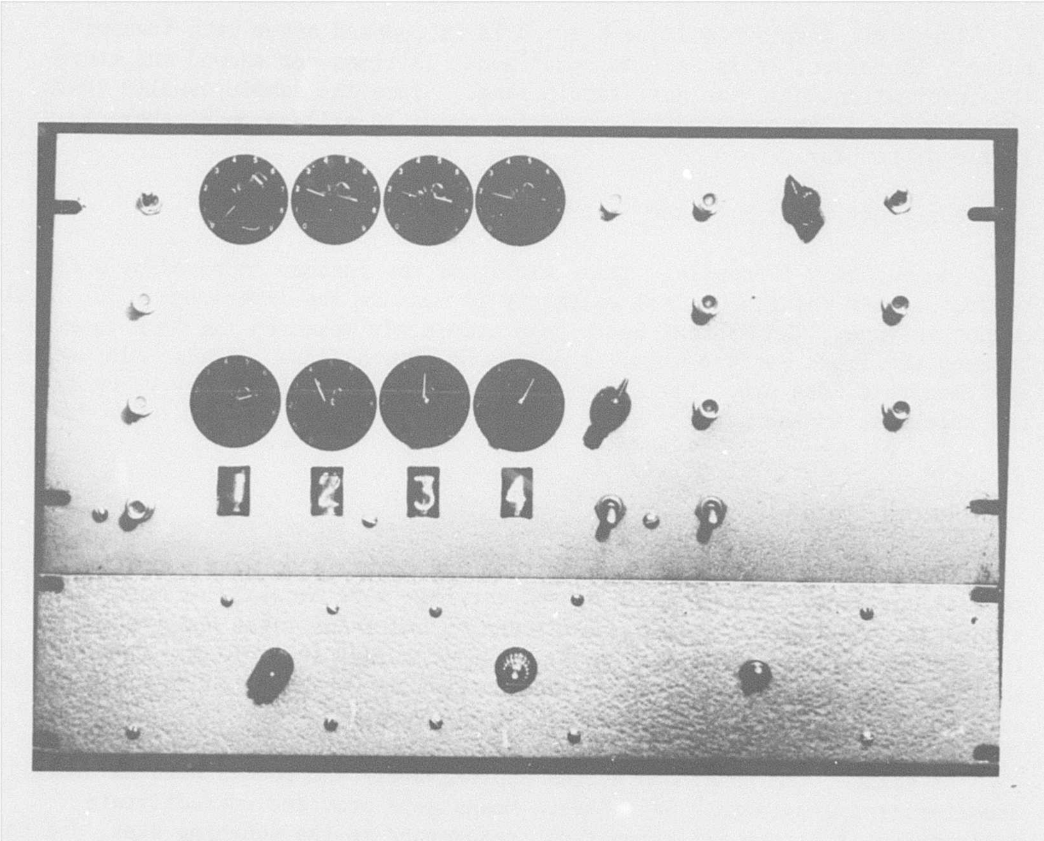


Figure 7. Digital Depth Gage Showing Numerical Readout

The Nixie display would be blurred if it counted after each transmit pulse. Therefore, it is made to count about 15 times per second and store the information until the next sample time. Since the sample usually takes less than 1 millisecond and is stored for about 70 milliseconds, there is little or no blur.

A circuit diagram of the instruments appears in appendix I.

The accuracy of reading signal amplitude was further improved by a digital readout system using a digital voltmeter to measure the Immerscope 725D's analog output voltage. The digital depth gage accurately measures the time interval between the front surface signal and an echo from a flaw. It also can measure specimen thickness precisely if velocity is known, or can measure velocity if the thickness is known.

Scan-Record System

The scanning transducer support tube and manipulator were supported on a movable carriage. The manipulator and carriage were manually or motor positioned at selected and synchronized scanning and index rates and increments. The scanner was supported over an 8- by 12-foot tank suitable for immersion or squirter coupling testing. The scanner drive was synchronized in a 1:1 ratio with an 18-inch direct-write Alden facsimile recorder.

As bonded, the rotor hub weighs approximately 400 pounds with an overall diameter of approximately 54 inches. Means were provided to facilitate positioning it in the immersion tank, referenced to the scanning axes, and to adjust the rotor axes so the inspection surfaces were normal to the transducer axis. A relatively simple fixture supports, positions, and levels the rotor hub (figure 8). The fixture supports the hub from either side by two types of attachment fittings. When the rotor hub is supported as shown, through transmission tests are possible. Reversing the rotor hub permits pulse-echo reflection measurements to be made without changing the transducer-scanner system. The 4-inch-diameter stainless-steel casters permit 360-degree rotor hub rotation for alining the scan axis. Two threaded jack sizes (6- and 16-inch) are available for leveling the rotor hub using a spanner wrench to turn the captive shaft fittings. The fixture is stainless steel except for the triangular iron pipe frame.

Calibration Standards

To produce meaningful ultrasonic data, many parameters or factors must be known or held constant. Each piece of test equipment in the system must be calibrated at intervals specified in the calibration schedule.

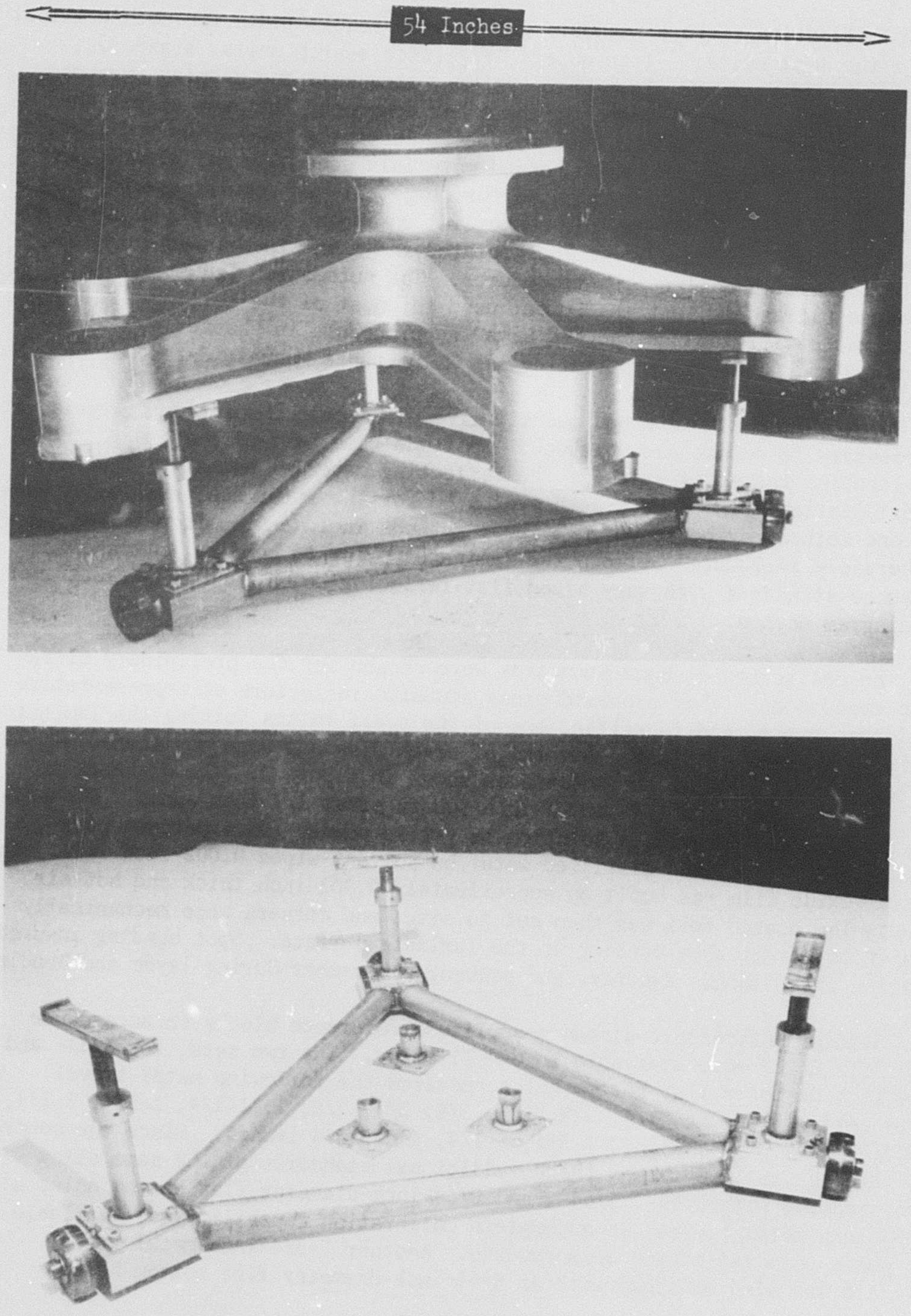


Figure 8. Ultrasonic Level-Positioner Fixture for H-53 Rotor Hub

Specifications insure standard calibration requirements for each critical item in the test system: transducers, reference search units, standards, transmitter and receiver electronic systems, time base and display systems, scanning and recording systems, or any other component that may affect the accuracy or interpretation of test results. Aerospace procedures and specifications for inspecting diffusion bonded materials generally differ only in minor respects. The need is stressed for competent and regular use of these specifications. In addition, the commercial equipment supplier's calibration and repair procedures should be incorporated and maintained as an integral part of the user's calibration procedures. The Automation Industries Model 725D Immerscope ultrasonic test instrument used for most of the testing in this program was calibrated and checked with the procedure in Chapter 4, Model 725 Immerscope and Accessories Operating and Maintenance Manual, dated October 1969.

To establish accurate and quantitative ultrasonic inspection criteria, it is necessary to relate acoustic echo amplitude-time test parameters to the size-location characteristics of the reflecting material anomaly. Several standardization methods have been evaluated for the rotor hub; eventually more than one method may be required. These methods include stopoff material deliberately introduced between the laminates prior to bonding, ultrasonic reference standards with vary-sized flat-reflector holes, and the Krautkramer AVG diagram method.

The deliberate disbond standards were chosen for the preliminary ultrasonic evaluation. They provided gross acoustic reflectors at representative metal thicknesses and identified one of the scarf joints joining the laminates in the same material plane. A total of seven disbonds were positioned within the hub during layup at the interfaces shown in figure 9. The disbonds at each location included 1/4- and 1-inch-square areas 1/2-inch apart. Disbonds were prepared by spraying a solution of yttria powder (99.9 percent pure), potassium silicate, and distilled water on solvent-wiped 0.002-inch foil. The yttrium-oxide film was built up approximately 0.002-inch thick and hot-air dried. The coated foil was then cut to size, and corners were mechanically scraped to permit spot bonding to the laminate surface. Spot bonding insured locating the disbonds exactly, and prevented movement during layup and bonding.

Standard ultrasonic distance-amplitude reference blocks in accordance with ASTM E 127 were available in 6-4 Ti alloy. The two sets, for 3/64- and 5/64-inch-diameter flat bottom holes, covered the following metal travel distances: 1/16, 1/8, 1/4, 3/8, 1/2, 5/8, 3/4, 7/8, 1, 1-1/4, 1-3/4, 2-1/4, 2-3/4, 3-1/4, 3-3/4, 4-1/4, 4-3/4, 5-1/4, and 5-3/4 inches. Since the central hub material is 12.5 inches thick, additional standards of the same alloy were procured with 3/64-, 5/64-, and 8/64-inch-diameter flat bottom holes at 6-3/4-inch metal travel, so a complete calibration capability was available for pulse echo reflection measurements. Another 5-3/4-inch metal travel standard was also obtained with an 8/64-inch-diameter flat bottom hole.

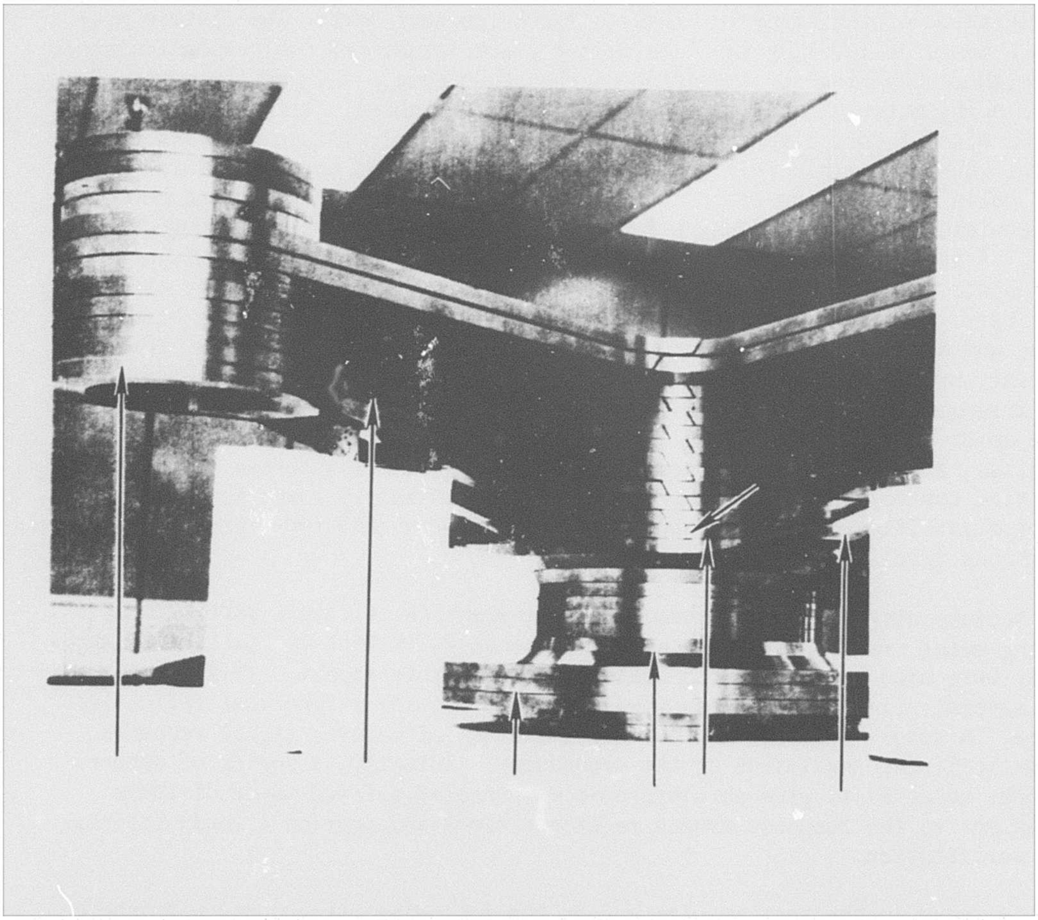


Figure 9. Location of Deliberate Disbonds in First Rotor Hub

A fixture for holding and alining ultrasonic standard blocks while testing the various hub sections was fabricated (figure 10) to easily adjust the elevation of the standard block to match the test part. The fixture provides a means of leveling the face of the block in each of two perpendicular axes without changing the elevation of the other axis. All working parts are noncorroding material that may be submerged in any normal ultrasonic test bath with or without corrosion inhibitor. The experimental fixture consists of several lengths of thin wall tubing supporting platforms and base plate. Two small balls fit in holes or indentations in the base plate and in another middle plate to let the middle plate tilt or pivot about a line through the balls. A second pair of balls is mounted between the middle plate and an upper plate. The center line through this pair is at right angles to the first pair. Threaded rods adjust the angle between the base and the middle plate, and between the middle and upper plate against the restraining force of a spring, providing independent leveling adjustments in the two axes. A split ring arrangement in the upper plate holds the standard firmly, but allows it to slide up or down to the desired elevation. The plates are phenolic, the balls are glass, a rubber band was used as the spring, and brass screws are used for adjusting controls. The aluminum tubing used for the platforms is coated with a protective film. A plastic bubble level mounted on the top plate provides a continuous level indication.

Because ultrasonic reference block alinement is critical, particularly on long metal travel distances, alternate sensitivity test and calibration checks were used in some of the measurements for this report. This technique uses several sizes of stainless steel balls to provide a spherical reflective source. A sphere presents a ready determination of maximum signal response without critical angulation of the transducer. Actually, a series of spheres could be selected to give an ultrasonic response at a fixed water distance equivalent to the response from a reference block and provide a ready calibration verification.

As noted in the test results and in the following paragraphs, ultrasonic inspection of scarf joint bonds is limited to only the first few laminate layers. Even those tests are considered relatively arbitrary because of the angle of the bond interface with respect to the upper plane surface of the rotor hub. An analogous condition exists in the arm ramp area and wherever metal flow occurred. The ultrasonic reflectivity of discontinuities at these interfaces is significantly affected and should degrade or possibly prohibit detection, depending on the discontinuity area, angle, and material depth. Several reference standards designed to provide quantitative measurements of these conditions used conventional pulse-echo reflection and through-transmission techniques, as applied to the normal inspection surfaces and from both the inner and outer diameter surfaces of the rotor hub. These include the following material conditions: (1) arm ramp standard - a series of six 4/64-inch-diameter flat bottom holes angled at 10-degree increments to a 1/4-inch depth in a 1/2-inch flat plate, (2) scarf joint standard - a series of five

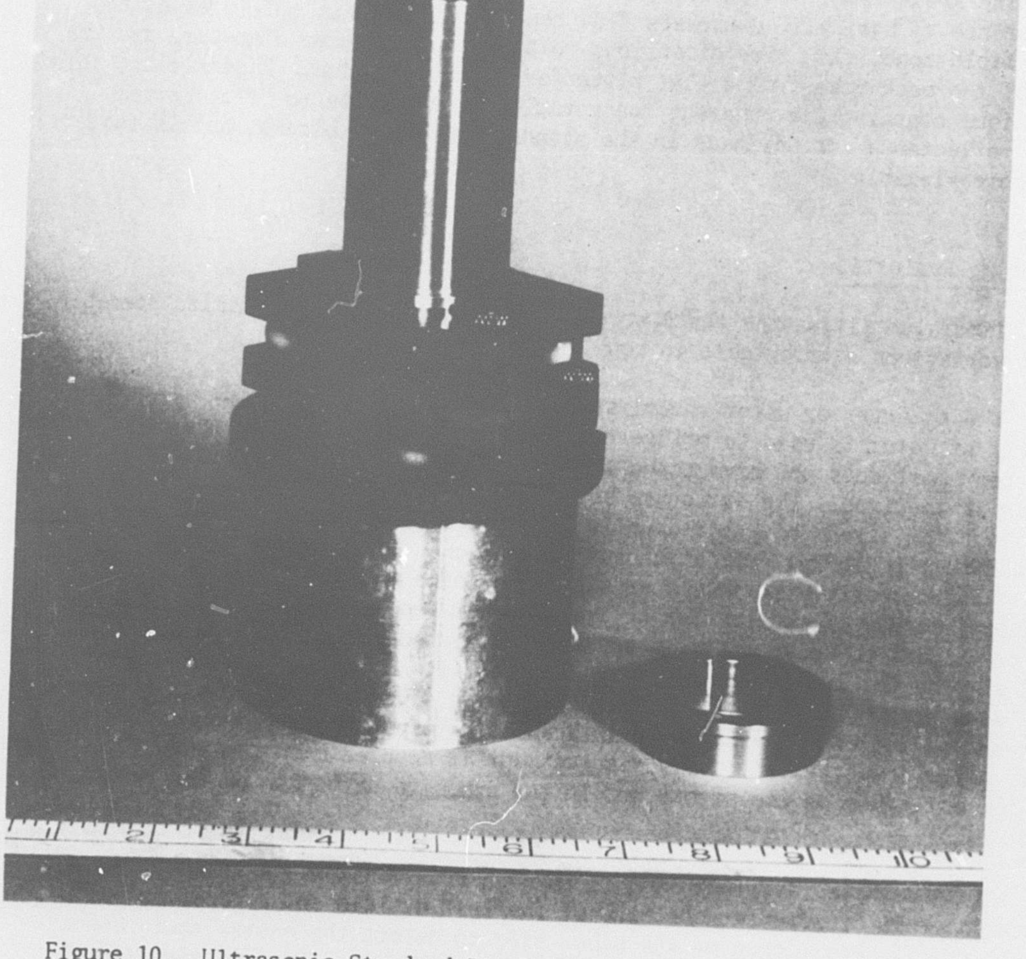


Figure 10. Ultrasonic Standard Block Positioning-Leveling Fixture

3/64-inch-diameter flat bottom holes radially located in a 2-1/2 inch thick ring with the same inner diameter as the hub; two series of five 3/64-inch-diameter flat bottom holes angled at 20-degree increments from the radial plane; a hole series at 1-inch and 2-inch depths in a 2-1/2 inch thick ring with the aforementioned diameter. Ideally, the material for these standards would be diffusion bonded rotor hub laminate stock; however, for the purpose of this evaluation, either titanium or steel material, whichever is available, was considered suitable since the acoustic properties are not significantly different. Photographs and drawings of ultrasonic standards for the rotor hub are included in appendix II.

The Krautkramer AVG calibration technique described in the literature (reference 4) basically expresses flaw depth dimensions as multiples of the near field zone, flaw size dimensions related to transducer diameter, and the use of the back echo from a flat plate for standardization. Essentially, this technique contains the inherent inaccuracies attributable to "flat bottom hole reflectance" criteria as in the standard reference blocks, but is faster and more flexible.

Coupling Evaluation

Immersion ultrasonic tests were generally performed to minimize possible test variations attributable to coupling variations.

The squirter or water column system also has been evaluated. A smooth stream of water is used to bridge the space between search unit and test part. The test part does not have to be submerged, and only a floor drain or catch basin is required. The structure being tested can be moved or positioned easily. The stream of water usually has a narrower cross section than the transducer, improving definition and resolution. Disadvantages in this system are reduced sensitivity and lower signal-to-noise ratio. Sensitivity is reduced because of the smaller active area between the search unit and test part. Signal-to-noise ratio is adversely affected by the loss of sensitivity, and also by the inevitable splash and instability of the water stream. When the scan system is operated at relatively high speeds, the stream of water is curved and introduces a lag or displacement between the recorder and the actual area being investigated. This displacement is doubled when the part is scanned in one direction on one stroke and in the opposite direction on the return stroke.

An alternate test technique is through-transmission. A transmitter transducer is directed at one side of the test article and a receiver transducer is positioned on the other side to detect the energy that passes through the part. If the material is continuous and solid, the signal will pass through unobstructed, but if there is a void or disbond, the energy does not pass through. This method gives no information on the depth of the discontinuity in the material and is useful only for rather large discontinuities.

Small discontinuities do not block a significant part of the beam and most of the energy flows around the obstruction. If the surfaces are not flat and parallel, the ultrasonic beam will be refracted and the transducers must be frequently repositioned.

A variation of through-transmission technique also evaluated employs a single transducer. The pulse is transmitted through the part, reflected from the back surface, and received through the same path.

Contact testing was used in some areas to study a particular location in detail. This technique has advantages in that the transducer can easily be moved to optimize the signal even in difficult locations. There is a minimum of beam spreading and attenuation, thus giving high sensitivity and good signal-to-noise ratio. Contact testing is not suitable for scanning systems and therefore does not lend itself to permanent recording. Because the surface of large diffusion bonded structures often is not regular or smooth, it is almost impossible to attain uniform coupling between the search unit and the part at all locations, even when manipulated by hand.

The relative acoustic coupling efficiencies of the manual couplant materials as listed here are based on the response of a 3/8-inch-diameter, lithium sulfate, 15 MHz transducer operated at 25 MHz on the 5/64 - 4-3/4 reference standard. The highest available frequency was selected because of increased test sensitivity to acoustic coupling properties.

Budd Company couplant No. 765	100 percent
Glycerine	100 percent
Industrial lubricating oil, SAE 30	85 percent

Based on this evaluation, pure glycerine was selected for the comparative transducer evaluation. Recently, another liquid couplant material tested appears to be superior to either glycerine or the Budd Company couplant. This couplant, a high-temperature lubricant marketed under the trade name Arcolor 1260, is manufactured by Monsanto Chemical Company. This couplant material proved to be employed as readily as other couplants and gave higher coupling efficiency in terms of signal amplitude. Another coupling medium evaluated was the NR-developed dry coupling material, which gave a zero-percent response at 25 MHz, an 80-percent response at 10 MHz, and a 100-percent response at 5 MHz. The dry couplant applicability appeared to be restricted not only in frequency but also to the smooth-ground surface of the reference standards. Manual coupling techniques are recommended only for limited inspections such as reverification tests, or where complete immersion tests are not practicable.

Transducer Evaluation

The wide range of ultrasonic transducers evaluated (table I) included immersion and contact types. The contact transducer evaluation used the Immerscope Model 725D pulser-receiver with several couplant materials. Data are based on the comparative signal response from a 5/64-inch-diameter flat bottom hole in a 4-3/4 and 5-3/4 inch metal travel Ti-6Al-4V reference standard. The Immerscope controls for damping, reject, display, etc, were held constant during the test.

Results of the comparative contact transducer evaluation are shown in figures 11 and 12. Detection sensitivity is in percent of full-scale signal response and in terms of instrument sensitivity setting necessary to give full-scale response. These comparisons clearly show a higher detection sensitivity for the lithium sulphate transducer and the applicability of the relatively larger diameter transducers operating at relatively low frequencies while maintaining a high detection sensitivity. Although a fairly good defect detection capability was demonstrated with the contact transducers, it is felt that the absence of a permanent record makes this test method less suited for production inspection except for spot checks, or where automatic scanning-recording facilities are not available.

An evaluation of the immersion-type transducers was made under exactly the same test conditions and reference standards described for the contact transducers, except for the 3-inch water bath coupling. As expected, detection sensitivity was significantly higher. Detection sensitivity for a 10 MHz, 3/4-inch diameter, flat focus transducer is shown in table II. The reflected signal amplitude was adjusted for full-scale presentation for each test at the noted receiver frequencies.

The 4-3/4-inch metal travel data are directly comparable to the contract transducer data. The 5-3/4-inch metal travel data obtained using a minimum of crystal damping showed a further increase in test sensitivity. In general, lithium sulphate or quartz crystals exhibit a low electrical Q and require little damping, while the ceramic type crystals exhibit high electrical Q and require maximum damping. Basically, the function of damping control is to minimize transducer ringing to permit resolution of reflectors close to the front surface of the test material. However, the damping control on most commercial instruments affects not only the ring time but also the amplitude of transmitter pulse, and adjustments must be carefully controlled to insure reproducible and reliable test results.

A detection sensitivity measurement was made of the 3/4-inch-diameter transducer using ultrasonic reference standards 3/64 - 6-3/4, 5/64 - 6-3/4, and 8/64 - 6-3/4 and a section of the rotor hub 5.98 inches thick with a 3/64-inch flat bottom hole. The hub standard was tested with the as-bonded surface and after surface grinding. Test results (table III) indicate an excellent

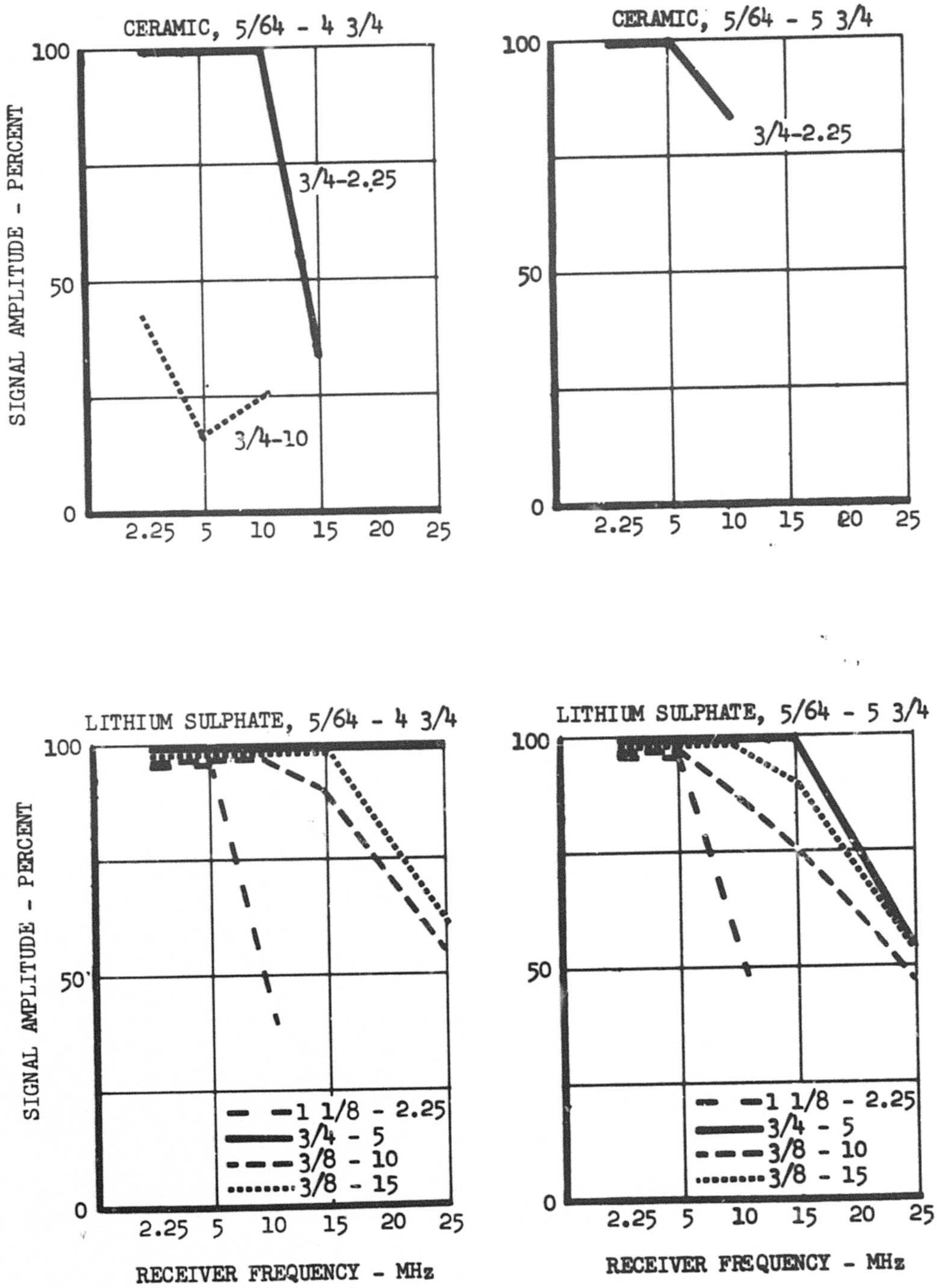


Figure 11. Ultrasonic Contact Transducer Evaluation Showing Response Amplitude Versus Receiver Frequency

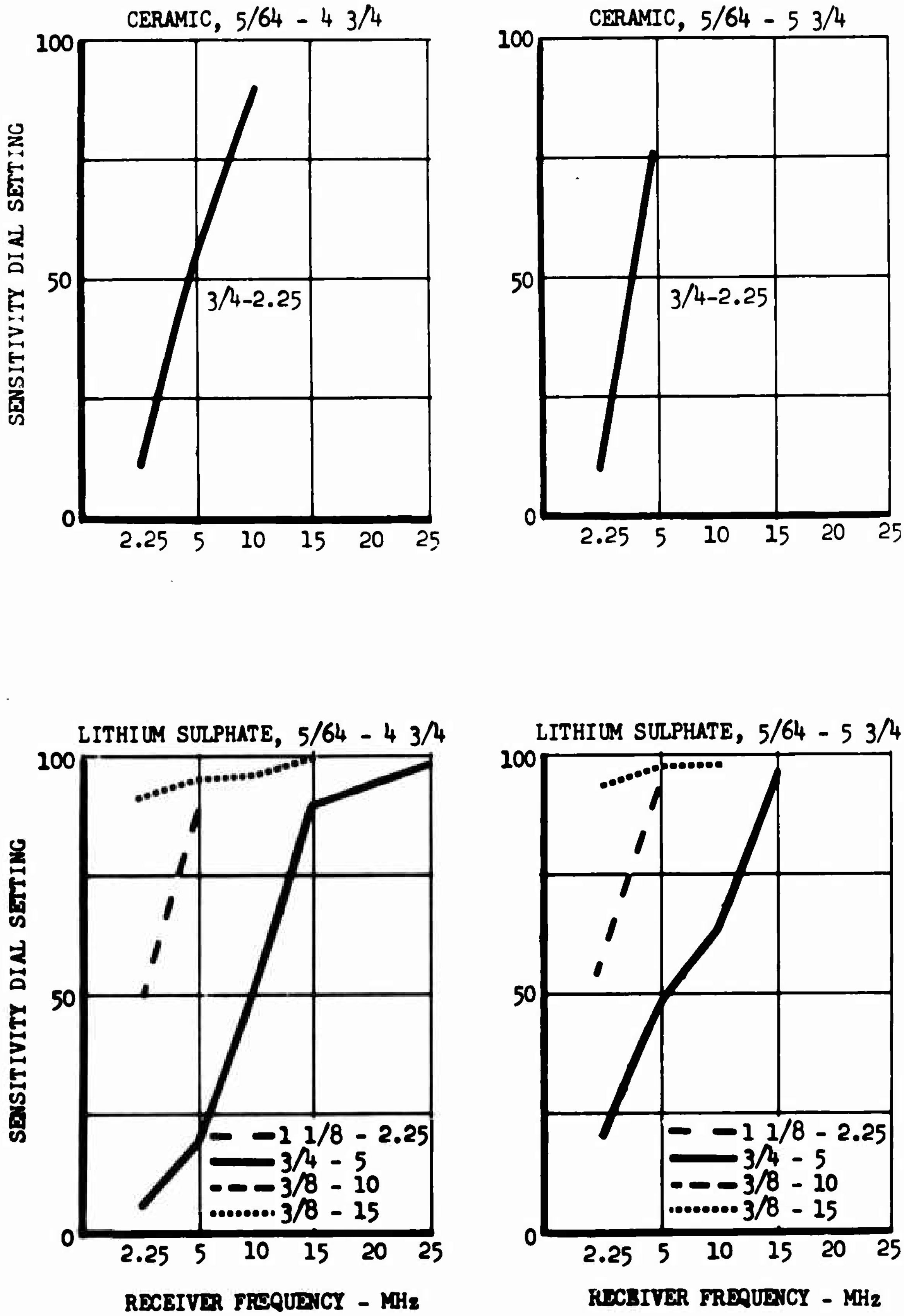


Figure 12. Ultrasonic Contact Transducer Evaluation Showing Test Sensitivity Versus Receiver Frequency

TABLE I. ULTRASONIC TRANSDUCER EVALUATION

Immersion Transducers

Type*	Frequency (MHz)	S/N	Focus	Diameter (Inches)
SIL	1	15891	Flat	3/4
SIL	5	14305	Flat	3/4
SIL	5	13108	Short	3/8
SIL	5	13109	Short	3/8
SIL	10	1193	Flat	3/4
SIL	10	98154	Flat	3/4
SIL	12	9540	Flat	3/8
SIL	12	9541	Flat	3/8
SIL	15	98162	Flat	3/4
SIL	15	957	Flat	1
SIL	25	16171	Flat	3/8
SIL	25	16172	Flat	3/8

Contact Transducers

Type*	Frequency (MHz)	Sperry(S) Magnaflux (M) Style	Diameter (Inches)
Ceramic	2.25	M-201543	1/4
SMZ	2.25	S-57A3042	1/2
SFB	2.25	S-50A2330	3/4
SFL	2.25	S-50K3607	1-1/8
Ceramic	5	M-201544	1/4
SFL	5	S-50K3586	3/4
SIL	10	S-50K3517	3/8
SFB	10	S-50K3597	3/4
SFL	15	S-50A2722	3/8
SFB	15	S-50K3498	3/4
SFB	15	S-50K3497	3/4

*SFL, SIL (lithium sulphate); SMZ, SFB (Ceramic)

TABLE II. DETECTION SENSITIVITY COMPARED AT SELECTED TEST FREQUENCIES

Receiver Frequency (MHz)	Sensitivity Setting: 5/64 Hole at 4-3/4 Inches (Damped)	Sensitivity Setting: 5/64 Hole at 5-3/4 Inches (Undamped)
2.25	7.6	2.3
5.0	7.9	3.5
10.0	7.9	3.3
15.0	8.9	6.4
25.0	9.6	8.5

TABLE III. SENSITIVITY TEST MEASUREMENTS

Standard	Receiver Frequency (MHz)	Response Amplitude Relative db
3/64 - 6-3/4	2.25	6.9
	5.0	10.6
	10.0	9.3
5/64 - 6-3/4	2.25	20.5
	5.0	16.7
	10.0	11.6
8/64 - 6-3/4	2.25	24.8
	5.0	19.5
	10.0	19.5
	15.0	11.4
6-inch hub section (as bonded)	2.25	25.9
	5.0	24.7
	10.0	23.8
	15.0	18.5
6-inch hub section (machined)	2.25	27.8
	5.0	25.6
	10.0	23.7
	15.0	20.1
	25.0	10.4

detection sensitivity, particularly at the higher test frequencies. The increased signal response level for the rotor hub material is due to the lower material attenuation as compared to the standard block.

The ultrasonic beam characteristics were evaluated for several transducers using the test system shown in figure 13. The transducer and a spherical target are immersed in a long narrow water tank. A lathe bed with an overhead framework is used to position the transducer relative to the target. The dividing head and transducer holder allow the transducer to be adjusted in elevation and in angular position along two axes, and adjust vernier lateral motion along the length of the lucite water tank. The lathe bed allows manual or motor-driven positioning of the tank in two directions, parallel and perpendicular to the length of the tank. Displacement in either direction can be plotted versus signal amplitude, using an X-Y plotter. In general, two types of beam characteristic should be determined. The beam profile is measured at discrete water path distances to give a family of curves to show how broad or narrow the beam would be as it scans a material defect at that distance. The target is also moved on the transducer axis to plot sensitivity versus water path along the centerline.

The profile characteristic is shown for a typical transducer in figure 14. At less than the near-field distance, there are multiple peaks or side lobes and the sensitivity on the centerline passes through alternate maximum and minimums.

All transducers evaluated had definite nonsymmetrical characteristics that could influence operator judgment in interpreting test results. The lack of symmetry is more evident at short water paths and usually is not objectionable at the near-field distance. Transducer selection should be based on the particular test conditions. Beam characteristics for each transducer should be well documented at the required test frequency. The focal length and depth of focus should be determined for focused units. For flat transducer units, the near field distance $\left(Y_0^+\right)$ should be known, as well as the range on either side of that distance for which sensitivity is constant within approximately 20 percent. This information should be measured, not calculated. Figure 15 records signal strength as a function of water path distance along the centerline of a typical search unit. Signal strength is relatively constant from 12 to 16 inches. For accurate testing, the gated range should be made to coincide with the flat portion of this curve. When the near-field distance in water has been established, the proper water path between the search unit and the metal will be:

$$\text{water path} = Y_o^+ - \text{metal travel} \cdot \frac{\text{velocity in the metal}}{\text{velocity in the water}}$$

Many search units do not have good beam symmetry as received from the manufacturer. The search unit selected should have a circular pattern and a minimum of side lobes.

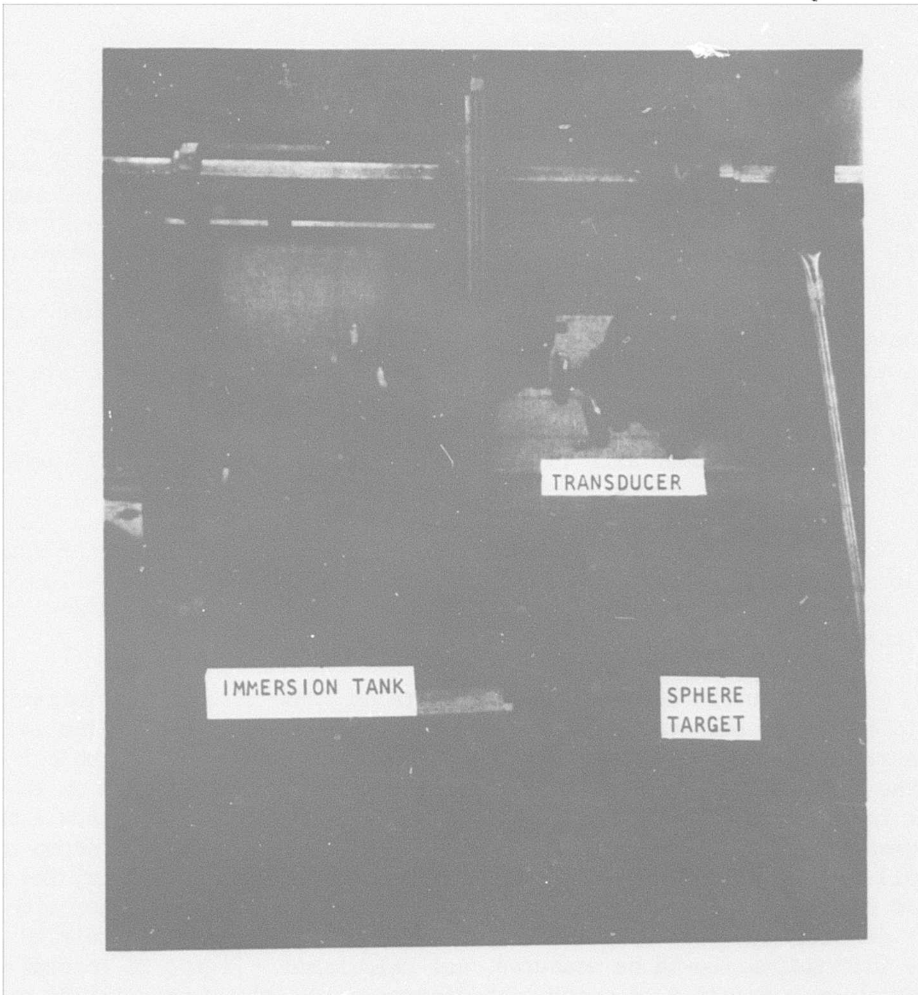


Figure 13. Ultrasonic Test System for Determining Transducer Beam Characteristics

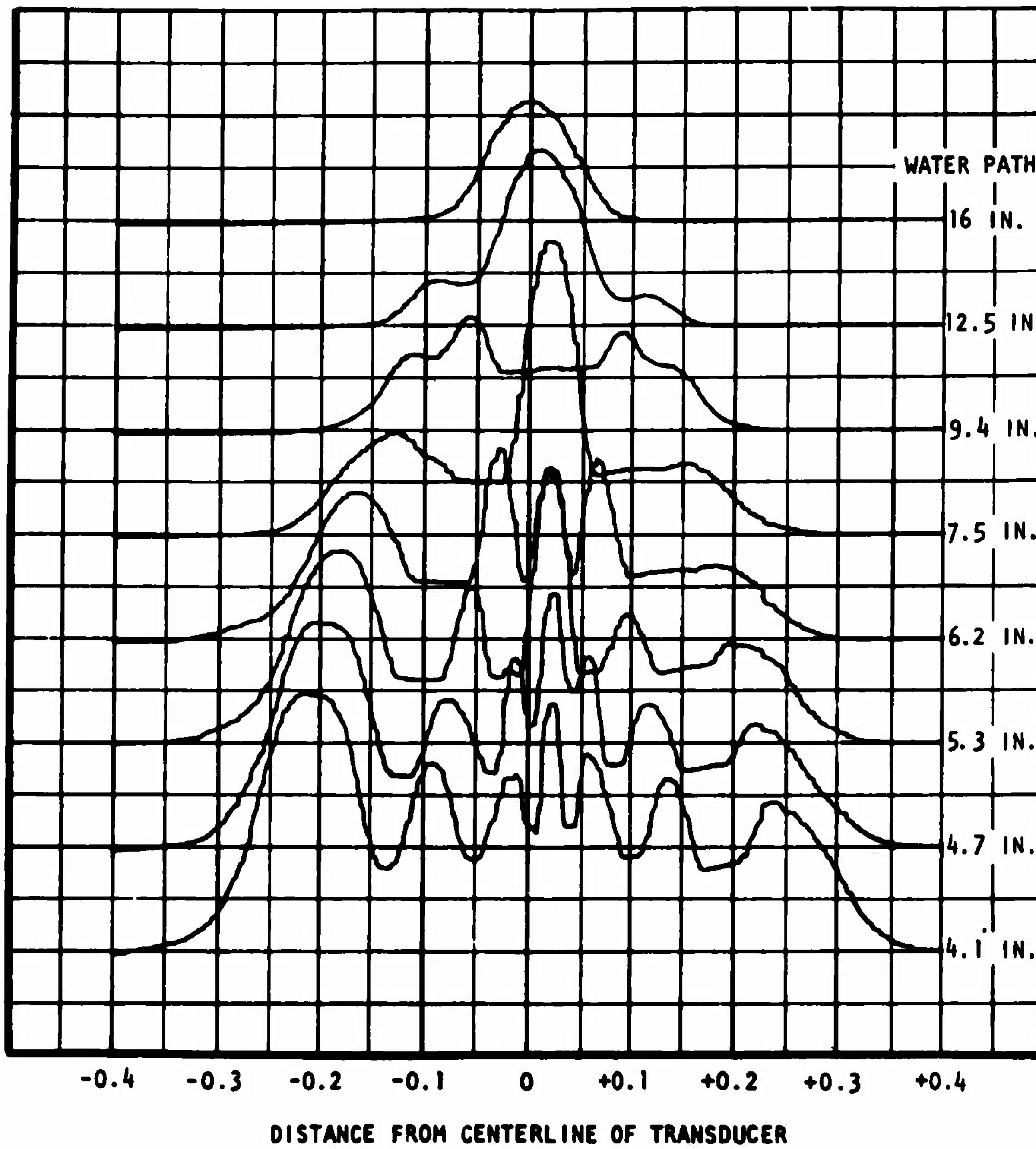


Figure 14. Typical Signal Strength Profiles of Transducer at Various Water Path Lengths

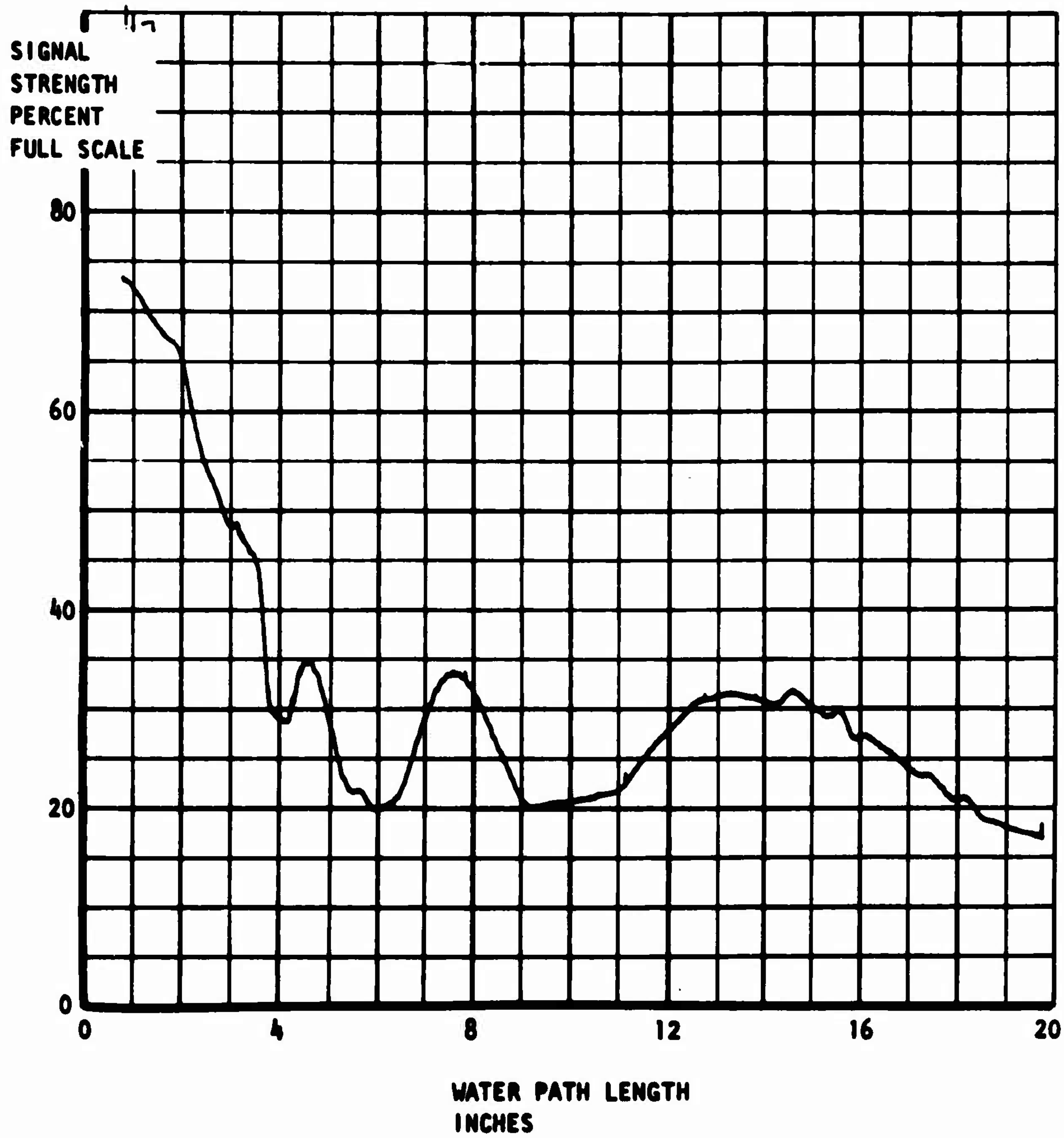


Figure 15. Signal Strength Versus Water Path Length on Centerline of Transducer

The frequency used for the test should be selected to give good compromise between penetration and resolution. High test frequencies are selected for optimum resolution, both in lateral position and depth.

Both the frequency (f) and transducer diameter (D) influence the near field distance as indicated by:

$$Y_o^+ = \frac{D^2 \cdot f}{4V_L}$$

where V_L is the longitudinal wave velocity.

To a great extent, transducer diameter determines beam diameter at the material surface. A small-diameter transducer will be more effective than a large one where the energy is to be channeled through a narrow member.

ROTOR HUB CHARACTERIZATION

Material Property Considerations

Metal characteristics (density, modulus, grain size, and homogeneity) determine ultrasonic velocity and attenuation within the metal.

The longitudinal velocity of the ultrasonic signal through a bulk material is dependent upon Young's modulus (Y), density (ρ), and Poisson's ratio (σ) of the medium, as follows:

$$\text{longitudinal velocity } \left(V_L\right) = \sqrt{\frac{Y(1-\sigma)}{\rho(1+\sigma)(1-2\sigma)}}$$

Velocity is important for several reasons. Knowing the velocity and the length of time required for a pulse to travel to a discontinuity and return, accurately determines the depth within the part. Using Snell's law, one also can predict and interpret the effects of refraction at an interface as follows:

$$\frac{\text{Sin } \theta_1}{\text{Sin } \theta_2} = \frac{V_1}{V_2}$$

where V_1 and V_2 are the ultrasonic velocity values for the two mediums, and θ_1 and θ_2 are the ultrasonic beam entry angles referenced to the two media. In this way, the ultrasonic beam can be angled into otherwise inaccessible areas. The beam also can be slanted to make it normal to a lamination interface not parallel to the entry surface. The acoustic impedance (Z_o) of a material is equal to the product of the velocity times the density of the material.

The impedance ratio between the metal and surrounding medium - or between two metals at an interface - will determine the proportion of the incident energy that passes through the interface and that reflects from the interface.

The transmission coefficient

$$T = \frac{4Z_1Z_2}{\left(Z_1 + Z_2\right)^2}$$

determines the amount of energy from the beam that will penetrate the test part and be useful in searching for discontinuities. It also determines the proportion of the reflected signal that will return through the surface of the part after striking an internal target.

The reflection coefficient

$$R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$

determines the proportion of the energy reflected from a discontinuity. It would be desirable to have similar impedances in the search unit, the coupling medium, and the test part. This would allow maximum transfer of energy and emphasize impedance differences between the test part and discontinuities.

As ultrasonic energy passes through a material, some energy is lost, causing signal attenuation. When a material is not perfectly elastic, some vibrational energy will be converted to heat. When dimensions of the metallic grain or crystalline structure become comparable to signal wavelength, the boundaries constitute interfaces that scatter the ultrasonic beam by reflection and refraction. Energy is dissipated, and the coherency of the beam is impaired. Porosity or surface irregularities cause similar attenuation.

Ultrasonic tests made on selected sections of the rotor hub established typical attenuation values. Tests also have been made to evaluate surface and beam effects. A 725D Immerscope display was used in combination with a 10 MHz Automation Industries 3/4-inch flat transducer. Several pieces of material selected from the hub were machined to flat parallel surfaces with thicknesses from less than 1 to about 6 inches. One test part was 0.87-inch thick machined from the flange arm. Another section from the center area of the arm was machined to have three steps 1.21, 2.04, and 3.03 inches thick. A third specimen, 5.98 inches thick, was taken from the center core area.

These parts were immersion tested with the receiver tuned to frequencies from 5 to 25 MHz, and water path was maintained at 6 inches. The results shown in figure 16 give signal strength of the first back surface echo. Signal strength decreases as the frequency increases.

Except for the 6-inch block, the signal level is higher for thicker parts than for thinner parts. Excluding material variables, this may be accounted for by the transducer being used well inside its near field zone. The measured near field zone for this search unit is 25 inches. Although the front surface water path is 6 inches for all specimens, each inch of metal adds approximately 4 inches of equivalent water path. The back surface is at an equivalent water path distance of 10 inches for a 1-inch-thick specimen, 18 inches for a 3-inch specimen, and 30 inches for a 6-inch specimen. This causes rather large variations in sensitivity. When the front surface water path is increased so all measurements are made in the far field, the additional metal path does not make such a great change in signal amplitude and the measured attenuations then fall in proper order.

For attenuation measurements, the back surface is used as the target and the plot of signal strength versus distance is not the familiar sharply peaked pattern obtained using a small target such as a sphere. Figure 17 shows the variation of the first back echo amplitude when a flat thin plate is observed at various water path distances. Beyond 12 inches, amplitude drops about 1/2 db per inch. This includes the effect of beam shape and water attenuation.

The transducer used for these tests has a very narrow beam at a distance of about 15 inches. When used to detect a 3/8-inch-diameter ball, the signal peaks sharply in an area about 1/8 inch in diameter and is relatively dead outside a 3/8-inch diameter area.

During ultrasonic inspection of the rotor hub, a significant echo amplitude variation was observed between front and back surfaces. This variation appeared to range from several db up to 10-12 db on the arm flanges which are nominally 1-inch thick. It was apparent that the gross signal variations were attributable to specific metal imperfections and projections on the flange surfaces. An investigation was made to further characterize the rotor hub surface, since rather small surface variations can make a large difference in the definition and apparent size of a defect located immediately below the surface. Two factors were of special interest: (1) surface roughness or texture; and (2) tooling contamination caused by an interaction between the restraining tooling and the rotor hub, varying from 0.001 to 0.008 inch thick. The ultrasonic characteristics of this contamination were not known. The surface roughness on the rotor hub was estimated to be nominally equivalent to a 125-microinch RMS machined surface. Surface roughness measurements made on an area 2 inches square ranged from about 100 to 275 microinches RMS.

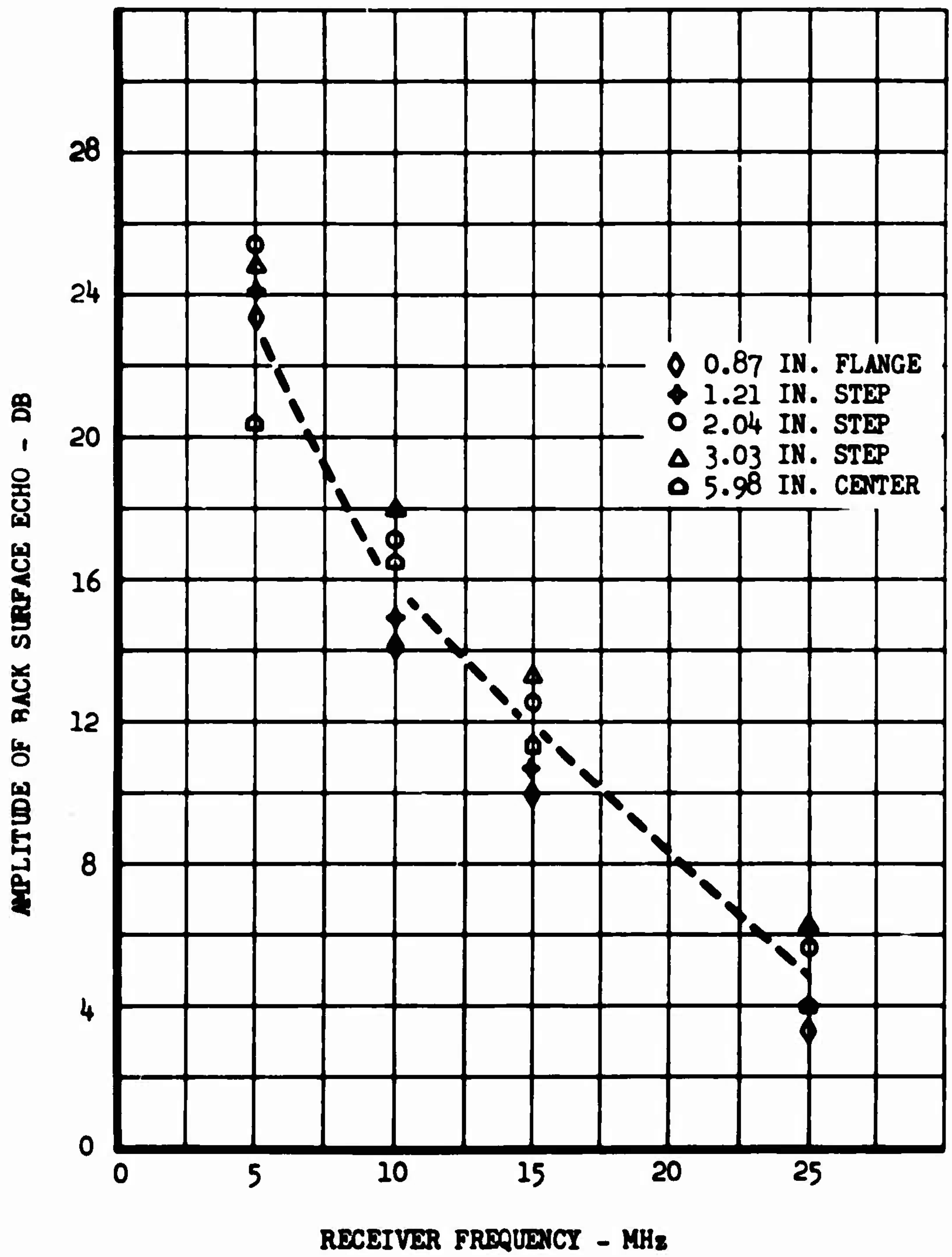


Figure 16. Attenuation - Test Frequency Relationship for Various Hub Section Specimens

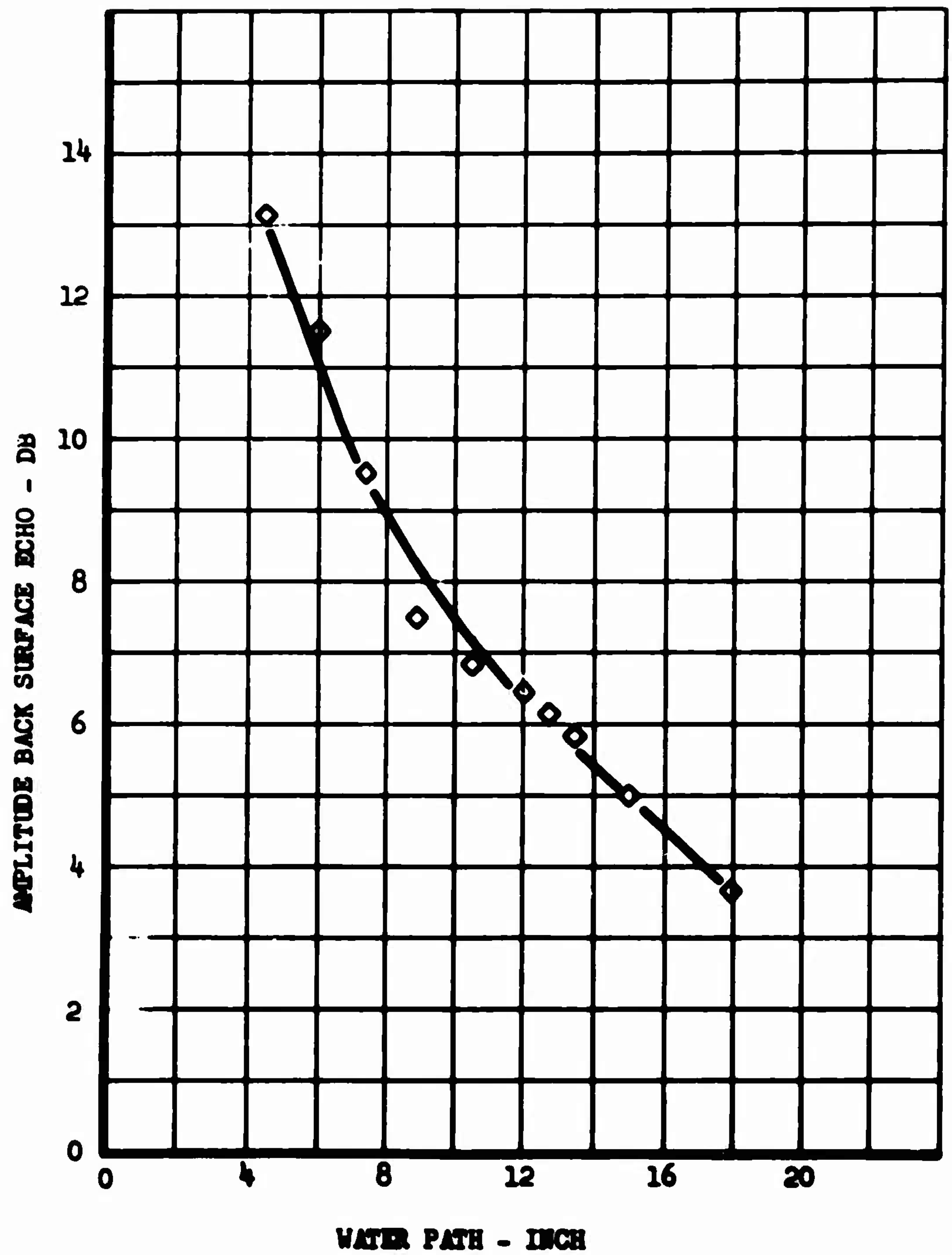


Figure 17. Variation in Amplitude of Ultrasonic Back Surface Signal with Water Path

Geometry Considerations

The rotor hub is a complex-shaped structure consisting of smooth and rough surfaces, concave and convex curvatures, thick and thin material sections, and other variables that significantly affect ultrasonic wave propagation. In many instances, the complex multiple beam reflection paths must be analyzed in three dimensions within the rotor hub. However, the specific test conditions were noted for all material areas where test ambiguity could occur and are described.

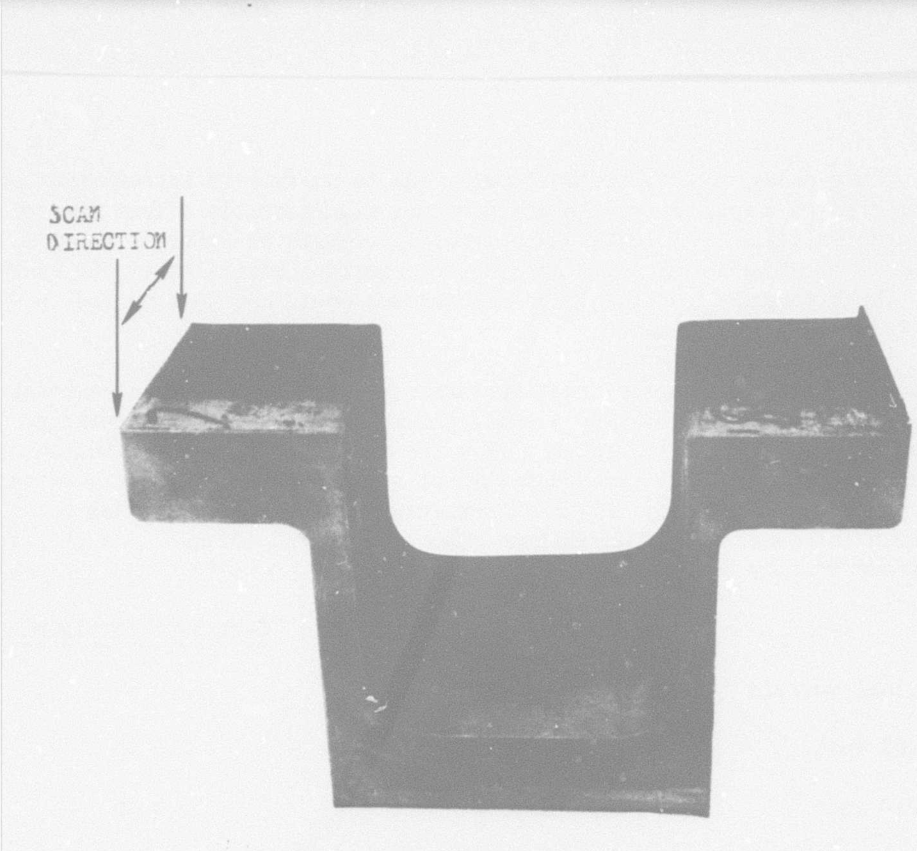
Each of these cases is elementary when it is understood and will be recognized by a competent operator who is careful to analyze the situation. Because of the hub's complex shape and size, these signals can be very deceptive.

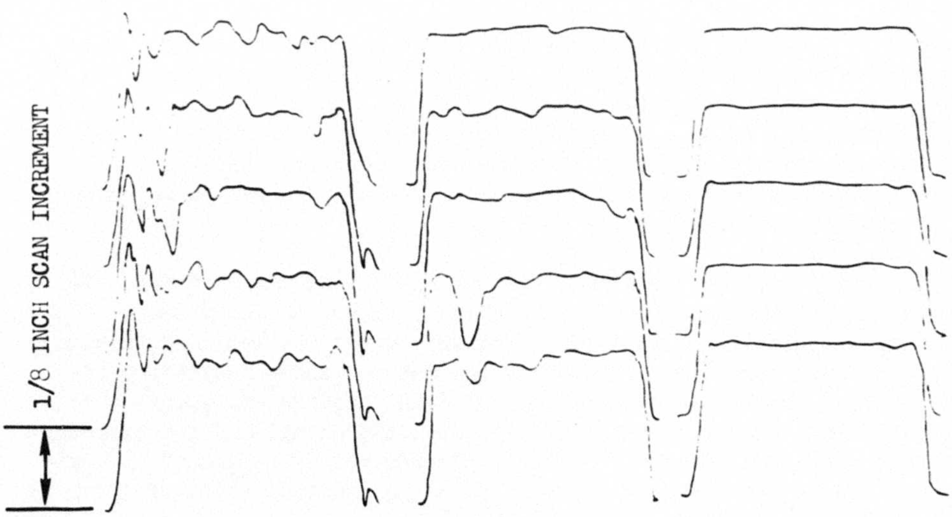
Several representative ultrasonic inspection conditions adversely affected by material geometry are illustrated in figures 19 through 21. Although each rotor hub condition must be individually analyzed, some general observations are noted for the conditions illustrated.

The ultrasonic transducer is normally scanned across the surface of the material to some convenient point beyond the edge of material. If there is a projection or rough area on the surface of the material beyond that edge, as shown in figure 19a, then a portion of the acoustic energy reflected through the water path to the transducer could be misinterpreted as a discontinuity occurring at the material edge. The apparent depth of the discontinuity is equivalent to approximately four times its actual depth due to the lower acoustic velocity of water. This condition was observed with projections in the 0.01- to 0.02-inch range.

If the ultrasonic transducer is scanned over a material including several material thickness, as shown in figure 19b, ambiguous data can be recorded due to multiple reflections. This condition occurs when the recording gate is set for an area several inches within the material; then a multiple reflection echo causes an apparent discontinuity indication in an area adjacent to the material thickness change.

The ultrasonic beam can be reflected in a number of directions by the flashing caused by metal flow at the material-tooling interface, as shown in figure 19c and d. The energy can reflect from one flash area to another. The acoustic waterpath produces an indication of an apparent discontinuity at an equivalent material travel distance. A variation of this condition occurs when the energy reflected from the second flash area returns directly to the transducer following a triangular path, or may even cause the beam to completely miss the transducer. In this case, the additional water path is equivalent to an additional material travel distance. Either of these paths can be detected by interrupting the acoustic beam with a pencil or other object at the locations noted.





(a) AS-BONDED SURFACE (b) FRONT SURFACE ONLY GROUND (c) BOTH SURFACES GROUND

Figure 18. Recordings of Ultrasonic Flange Response from Back Surface of Hub Flange Showing Effect of Surface Preparation

The phase delay of an ultrasonic pulse due to surface variations that are small compared to a quarter wavelength does not significantly affect the reflected pulse characteristics. At 10 MHz, a quarter wavelength in water is about 1,500 microinches, or a loop path corresponding to a surface variation of 750 microinches. Thus, roughness of the rotor hub surface would not be expected to cause ultrasonic interference.

The amplitude of both the front-surface echo and the first back-surface echo was improved considerably by a small amount of polishing or smoothing. Fine emery paper was used to remove a very thin layer of material. Polishing 0.0005 inch from the face increased the front-surface echo by 1 db (10 percent) and the back-surface echo by 1/3 db (3 percent). Polishing to a total of 0.0015 inch increased the front-surface echo by 2 db (20 percent) and the first back-surface echo by 1 db (10 percent).

	Front-Surface Signal	Back-Surface Signal
Original surface	0 db	0 db
0.0005 inch	1.1 db	0.3 db
0.0010 inch	1.7 db	0.8 db
0.0015 inch	2.0 db	1.0 db

Waviness is a surface variation similar to roughness but having a much larger average distance between crests. The depth of these variations can be much greater than the measured roughness figure, and could approach the half-wavelength dimension. This could account for very large changes in signal strength from one area to another. It would seem, however, that the emery cloth would follow the contours of the wavy surface and remove approximately equal material from all areas of the part.

A segment of flange on the arm of the hub was scanned at intervals of 1/8 inch from the edge. The amplitude of the first back-surface echo was used as the reference. Figure 18a shows a record of this amplitude measured through the original surface, and shows the variations due to random scattering and diffusion. Figure 18b was recorded after the front surface was machined to a smooth finish. Much of the random variation was eliminated, and the back surface was shown much more clearly. Signal amplitude was increased by approximately 2 db. Figure 18c shows the very uniform amplitude of the target signal when the back surface had also been smoothed.

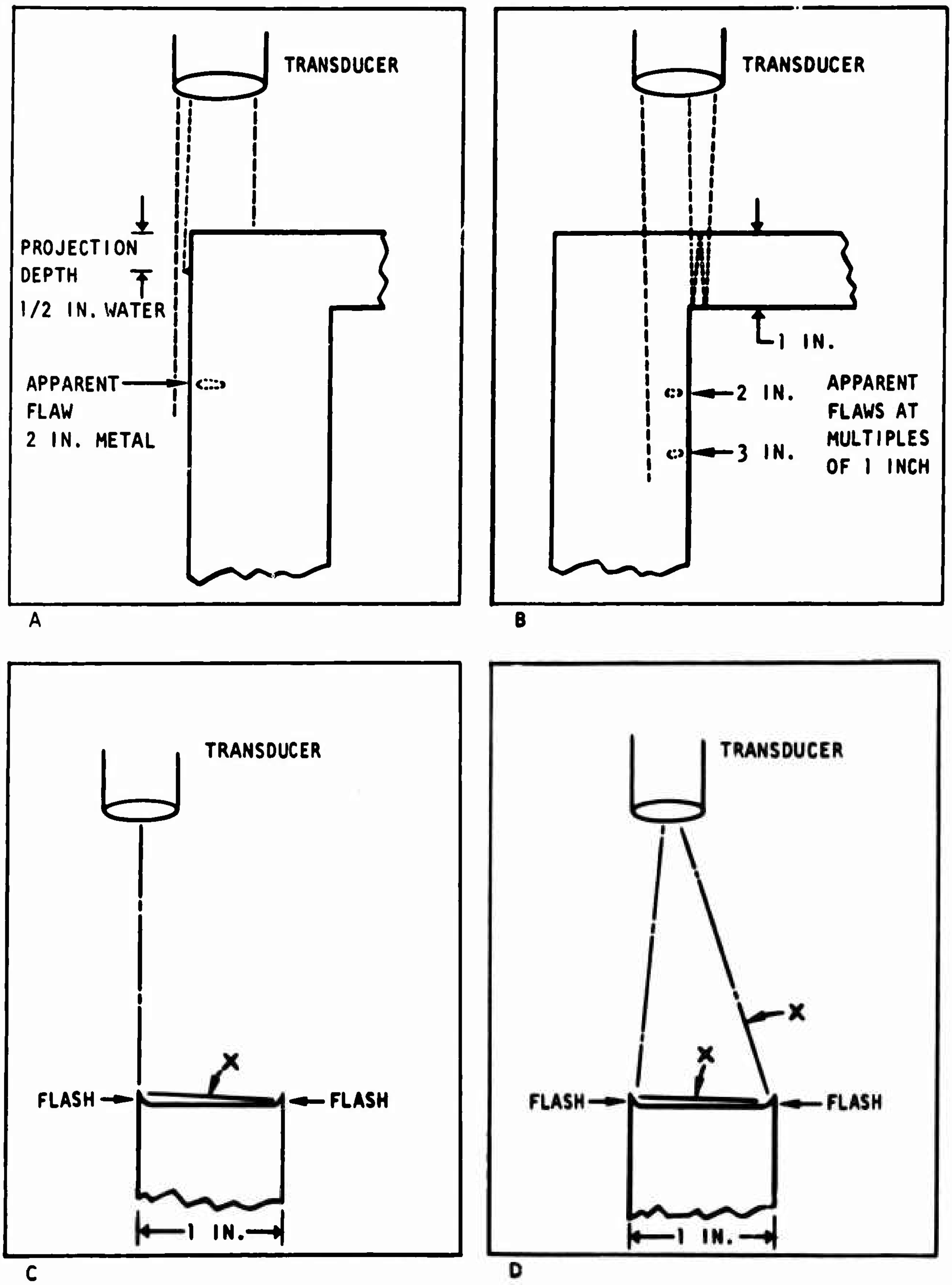


Figure 19. Illustrations of Geometric Considerations

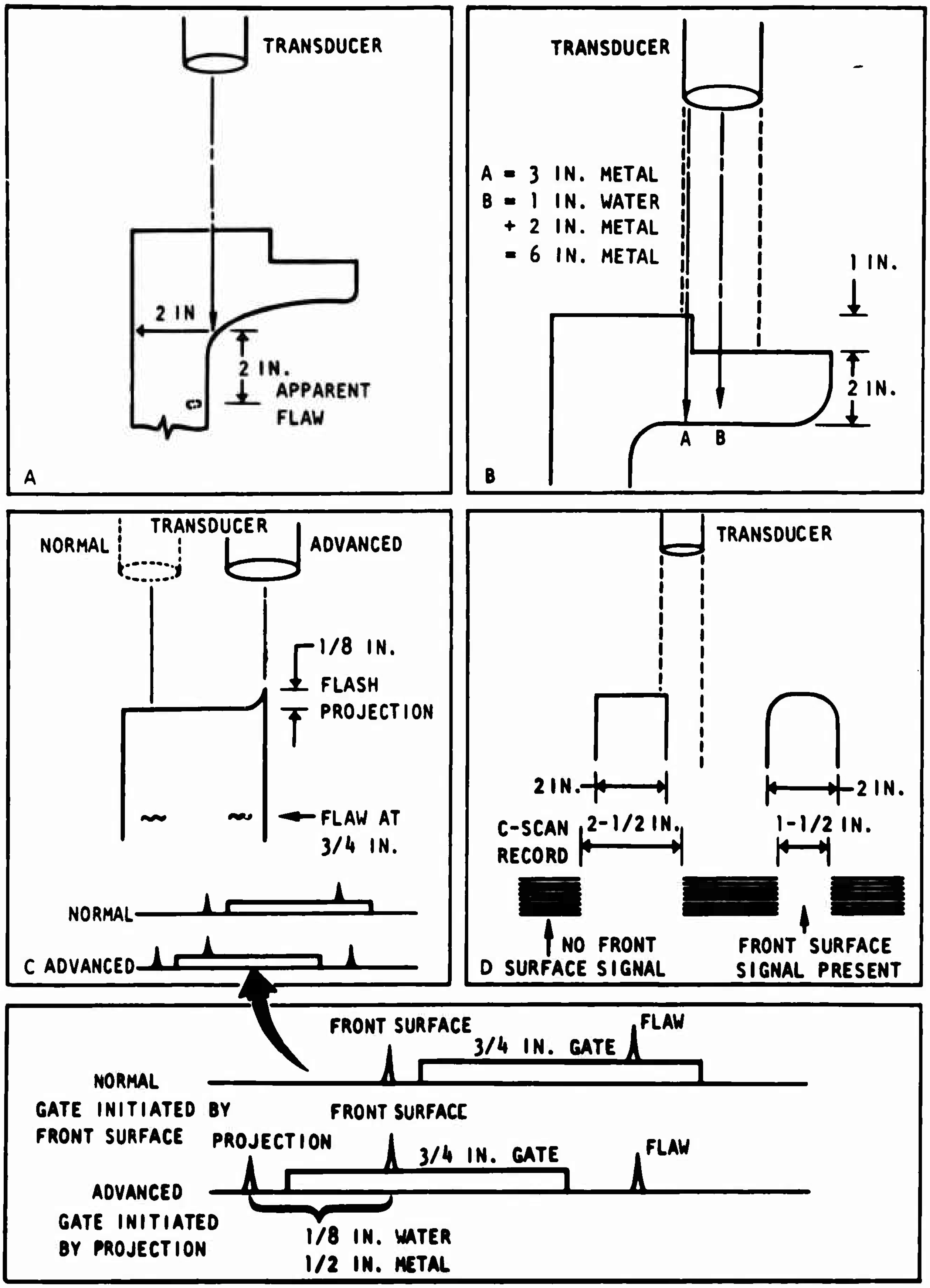


Figure 20. Illustrations of Geometric Considerations

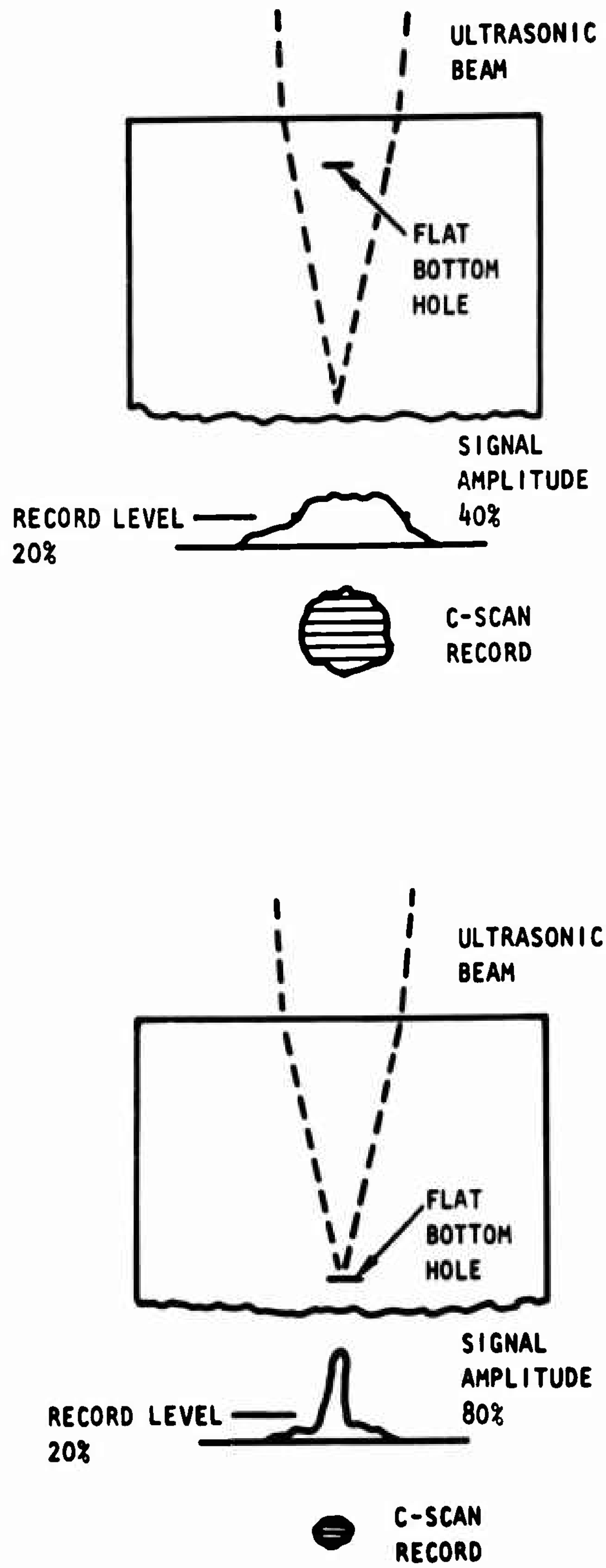


Figure 21. Illustrations of Geometric Considerations

An acoustic beam that strikes a fillet or other curved surface may be reflected to an external surface and return giving a false signal that appears to be deep within the material as shown in figure 20a.

An analogous condition is shown in figure 20b, where a small portion of the acoustic beam strikes a step in the material. Although the metal travel path is longer, the back surface echo will be reflected early and recorded to show a false indication in the area of the material step.

Ultrasonic tests frequently use the front surface signal to synchronize the recording gate circuit using the video sync signal. Ultrasonic readings made near the surface of a material require that the recording gate be started very shortly after the first video or echo is detected. The front surface reflection should not fall inside the gate. When a small projection such as flashing rises above the front surface, it can trigger the gate earlier than normal, as shown in figure 20c. The front surface signal from the material then falls inside the gate and is recorded as a discontinuity. Since the velocity in water is about one-fourth that in metal, a 1/8-inch projection advances the gate by the equivalent of 1/2 inch of metal. A 1/4-inch projection can cause all signals to shift 1 inch relative to the gate, and they may jump into or out of the gate giving false information at any depth.

Ultrasonic instruments using "edge marker" systems depend on the detection of a front surface signal. Ambiguity can occur when the acoustic beam has an appreciable width and in those conditions where a large front surface signal occurs, even after the center of the transducer has traversed the edge of the part (figure 20d). For these reasons, the "edge marker" type systems are not necessarily an indicator of part location on C-scan recordings. The recorded outline is usually larger than the part. For a more accurate outline of the material on the record, the threshold of the edge writing circuit should fall at the level where half the area of the acoustic beam impinges on the part, although some distortion will occur at the corner of the part.

If the ultrasonic beam does not strike the specimen normal to the surface, it will be refracted within the material in accordance with Snell's law. The beam can be normalized properly on one part of the surface and not on another. The refraction can easily cause an echo to appear at the wrong point on the record, whether it be a flaw signal or one of the reflections previously mentioned. The operator must guard against this possible source of error.

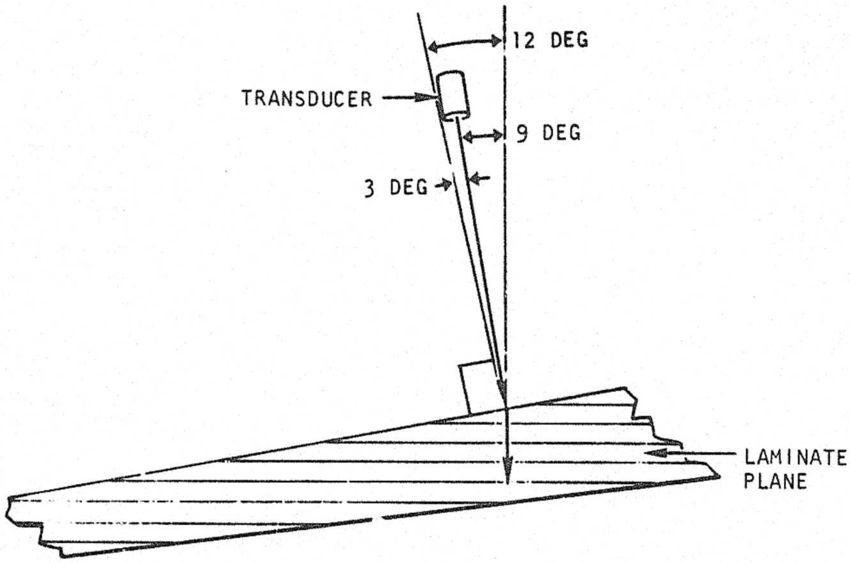
When the surface planes of complex or large material are not parallel, they may cause the acoustic beam to be refracted within the material, in accordance with Snell's Law. This refraction can cause false indications due to multiple or unknown reflections within the material, or simply by transposition of actual acoustic indications.

The energy pattern and shape of the beam from a transducer has a strong influence on the sensitivity and resolution of a measurement. Consider the same transducer and the same water path, but two flat bottom hole standards or two identical flaws at different depths within the metal. One might expect the target nearest the surface to give the greatest signal strength and best resolution, because of the shorter path for attenuation and scattering to take place. This is not necessarily true. In an actual case, a 5/64-inch standard 1/2-inch deep gave 60 percent signal amplitude and recorded as a 1/2-inch-diameter spot, while a 5/64-inch standard at 2-3/4 inch depth gave 100 percent amplitude but recorded only a 1/4-inch diameter. Figure 21 shows a probable reason. The 1/2-inch standard is situated at a distance much less than the near field distance where the beam pattern is very broad, but has no high sensitivity peak. The 2-3/4 inch standard is nearer the optimum distance and provides a narrow, high sensitivity zone, and gives much greater signal amplitude over a rather small area. The search unit should be used at approximately the near field limit whenever this is possible. Where a flat bottom hole standard is used to evaluate the size of a discontinuity, both the standard and the flaw must be at approximately the same point in the beam pattern.

A rotor hub contains many curved or fillet areas. Some of the fillets cannot be reached by a beam normal to any flat surface. By tilting the beam slightly through a known angle, however, it can be directed into nearly every part of the fillet. The few small spots not covered by this process can be inspected by hand scanning them from the curved surfaces. The length of the metal path from the flat beam entry surface is not constant. This problem can be overcome by making several records at various depths or by hand scanning.

Most hub areas can be inspected from a surface parallel to the major plane of the hub and the thickness of material is fairly constant for any one record. One exception is the ramp or floor of the arms. As seen in figure 22, both ramp surfaces slope, one at about 9 degrees and the other at about 12 degrees relative to the major plane of the hub. Thickness varies from about 7/16 to 1 inch. The video sync circuit in the ultrasonic equipment can be used to correct for changes in the water path to the front surface of the material, or the rotor hub can be tilted to make the front surface level with the scanner. The width of the record gate can be manually adjusted by the operator as the transducer is indexed along the length of the rotor hub arm, keeping the gate limits just inside the front and back surface signals. This method proved difficult to perform for extended test periods. A method for automatically programing or correcting the recorder gate was considered and is discussed in the following section.

Ultrasonic inspection procedures are applied in a manner to detect discontinuities occurring anywhere within the diffusion bonded structure. If one assumes that the integrity of the individual laminates has been verified though nondestructive and mechanical property measurements prior to assembly and bonding, then subsequent inspection must concentrate on the efficiency of the



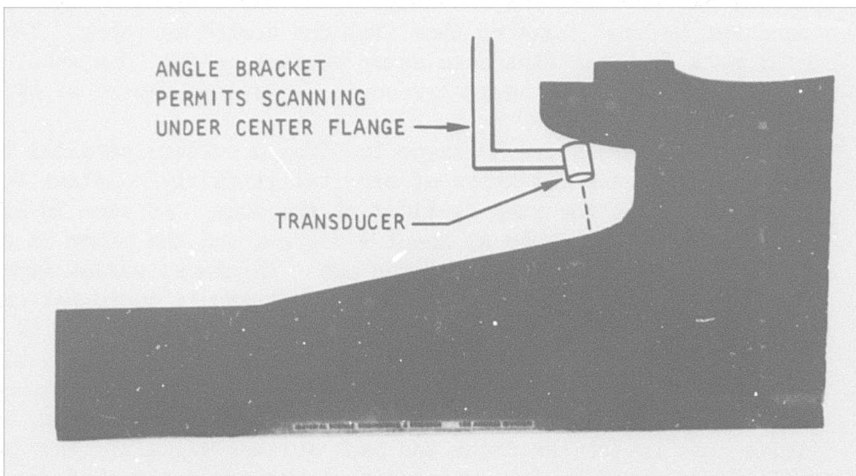


Figure 22. Beam Normalized to Laminates in Ramp

bonding process. In particular, inspection should insure that no discontinuous conditions exist at the bond interfaces.

During bonding, the laminations may undergo plastic flow and the interfaces may remain essentially flat, or they may assume an angle to their original plane. The optimum ultrasonic test conditions exist when the acoustic beam is normal to an acoustic reflector such as a discontinuity. It is desirable to have the ultrasonic beam normal to the interface, but frequently the position of the interface is not known.

Even if the plane were known, it is not always possible to aim the beam normal to that plane. The hub contains some interfaces or scarf joints between plates, intentionally inclined 60 degrees to the plane of the hub. Inspection of these scarf joints is difficult since there is no flat surface from which an ultrasonic beam can enter the hub and be normal to this interface.

To diffract an acoustic beam normal to the scarf joint areas, the entry must be displaced approximately 1.7 times the penetration depth. When inspecting laminates deeper than approximately 2 inches, that requirement places the beam entry point beyond the hub surface. Two alternate techniques are being considered:

1. An oscillating or nodding transducer manipulator could be used to scan the anticipated angularization of the displaced bond interfaces and some of the scarf joints. A number of welding torch manipulators are available for this evaluation and could be adapted to accommodate an ultrasonic search tube. Other variations could include an automated echo maximizing and location system.

2. Various forms of the Automation Industries Delta inspection technique could be employed using both fixed and scanning transducers located on the hub sides and/or bore areas.

ULTRASONIC TEST RESULTS

Rotor hub No. 1 was ultrasonically tested to determine the feasibility of detecting the disbonds introduced deliberately. These tests demonstrated that all 1-inch-square disbonds could be detected and were located as planned. The hub assembly was sectioned for mechanical property testing; then representative sections, including the deliberate disbonds, were designated for detailed ultrasonic inspection. Specimen surfaces were etched with an oxalic-hydrofluoric acid solution to precisely locate the bond lines. It was found that this could be satisfactorily accomplished on the as-bonded specimen surface. The spacings between bond lines at the surface were measured to precisely identify the depth of ultrasonic indications.

Results of the ultrasonic evaluation are summarized in table IV. It is emphasized that these results show the test limitations based on available transducers and conventional techniques. Representative ultrasonic C-scan recordings are included for the 6-inch-thick hub center (figure 23) and the 4-1/2 inch thick lug section (figure 24). A scaled photograph of the sections tested is also illustrated. The test conditions are based on longitudinal wave mode using squirter and immersion coupling. Inspection sensitivities, in most instances, are equal to or better than the maximum allowable disbond conditions for current diffusion bonding inspection specifications.

A complete set of ultrasonic test conditions, test data, summary of test results, and ultrasonic C-scan recordings appears in appendix IV. These data are considered to be of specific interest to ultrasonic inspections concerned with evaluating the H-53 helicopter rotor hub structures. Further, the data illustrate generally the magnitude of the rotor hub inspection task and the need for systematic and accurate inspection data recording and analysis.

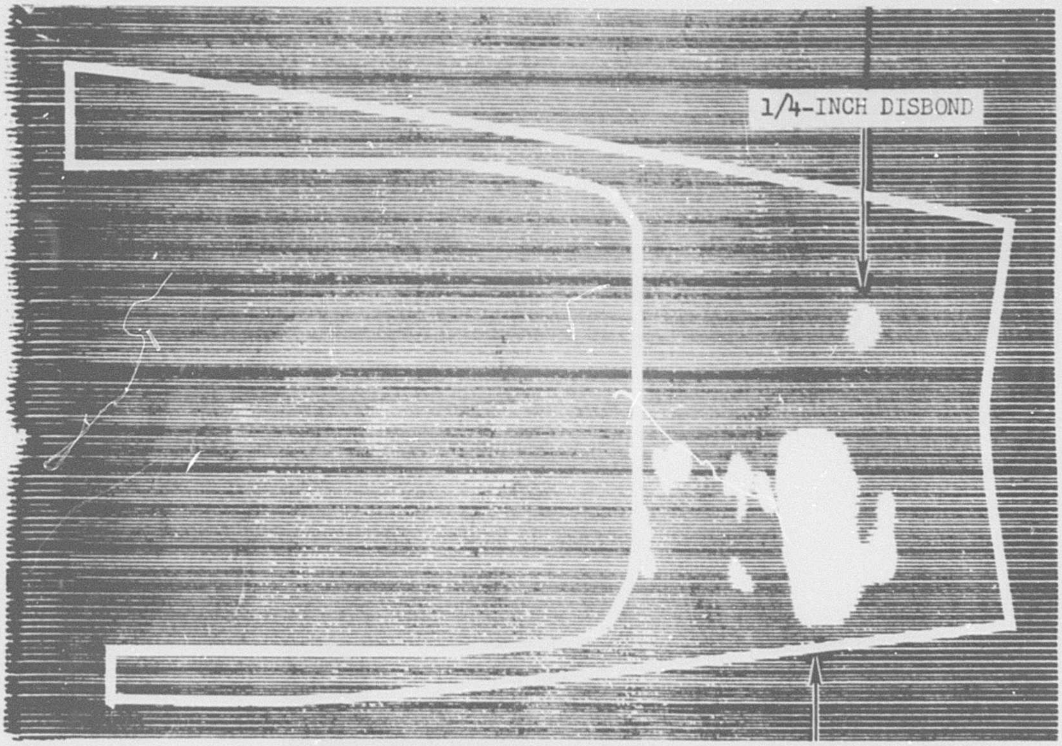
The minimum size of discontinuity that can be measured varies with location, depth, orientation to the inspection surface, and the type of discontinuity. Very small disbonds (equivalent to a 3/64-inch flat-bottom hole or smaller) can easily be detected within 2 or 3 inches of the front surface. At depths of 6 or 7 inches, because of noise level and attenuation, the threshold of detection approaches the equivalent of a 1/8-inch flat-bottom hole.

TABLE IV. REPRESENTATIVE TEST PARAMETERS AND RESULTS

Inspected Location	Gated Metal Travel (Inches)	Threshold Level*	Largest Signal Recorded**	Transducer Dia (Inch)	Transducer Freq MHz	Receiver Frequency (MHz)
Arm flange	1/4 to 1/2	2/64	6/64 at 1/2 in.	3/4	10	2.25
Center flange	1/2 to 1-1/8	2/64	3/64 at 1 in.	3/4	15	2.25
Arm wall	1/2 to 1-3/4	2/64	3/64 at 1-1/8 in.	3/4	15	2.25
	1-3/4 to 4-1/4	3/64	3/64 at 1-3/4 in.	3/4	15	2.25
	4-1/4 to 6-3/4	3/64	4/64 at 5-3/8 in.	3/4	15	2.25
Lug	1/2 to 2-3/4	2/64	3/64 at 1-1/8 in.	3/4	15	2.25
Arm ramp	Variable	2/64	None recorded	3/4	15	2.25
Center	1/2 to 6-1/2	3/64	5/64 at 4-5/8 in.	3/4	15	2.25

* Approximate recording threshold in terms of equivalent flat-bottom hole standards

**Largest signal recorded in terms of equivalent flat-bottom hole standard at depth indicated



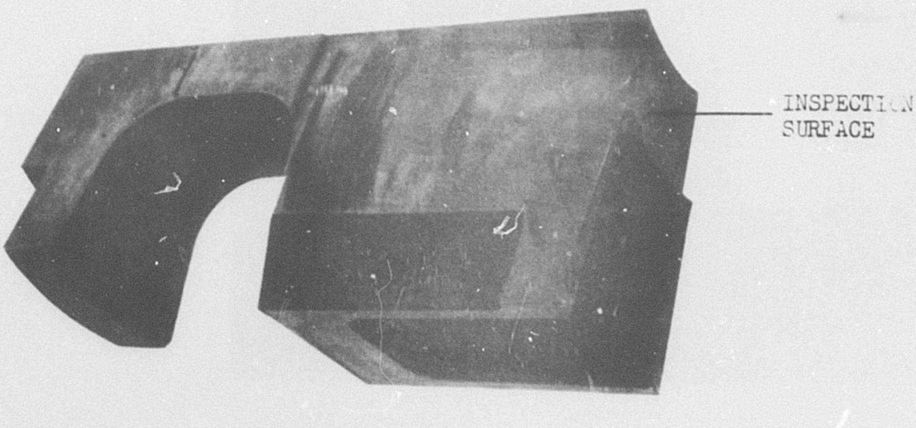
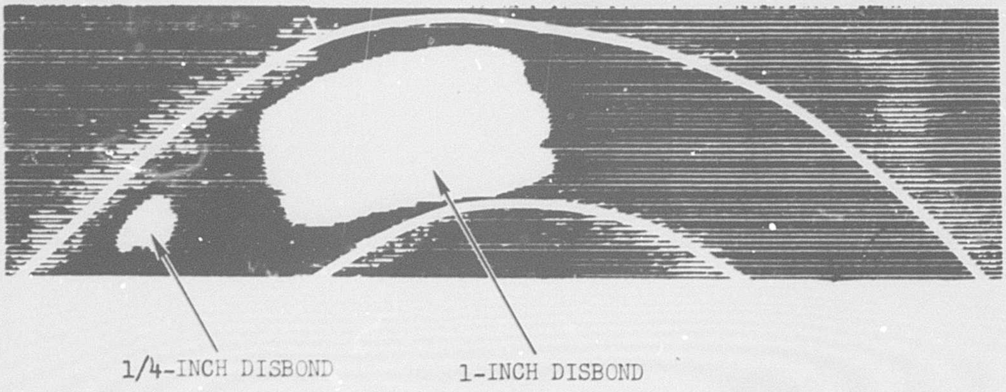


Figure 23. Ultrasonic C-Scan Record of Deliberate Disbond Located at 6-Inch Depth in Hub Center Section; Transducer: 10 MHz, 3/4-Inch Diameter; Receiver Frequency: 2.25 MHz



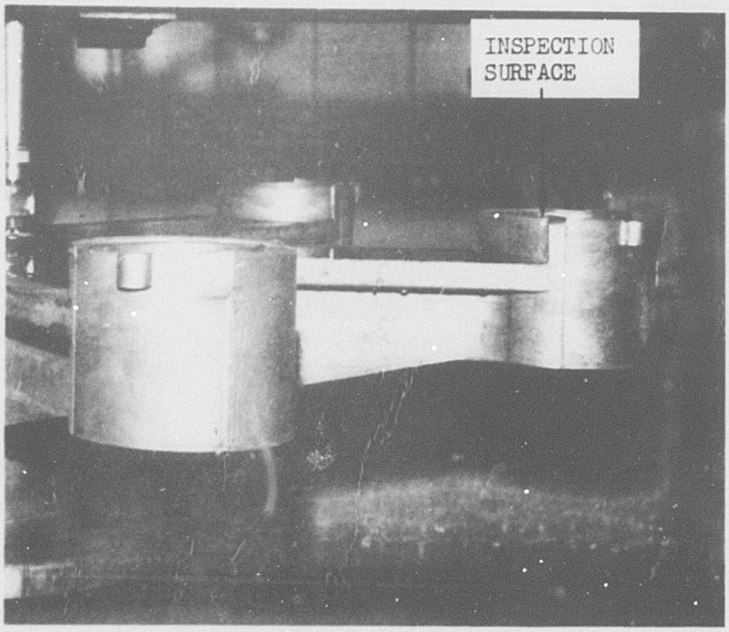


Figure 24. Ultrasonic C-Scan Record of Deliberate Disbonds Located at 4-1/2-Inch Depth in Hub Lug; Transducer: 12 MHz, 3/8-Inch Diameter; Receiver Frequency: 2.25 MHz

Measurements made to detect an intentional disbond introduced into one of the scarf joints 2 inches below the surface indicate that the transducer gives greatest response signal amplitude when the angle of incidence to the top surface is about 8 degrees. The scarf joint is about 60 degrees from parallel with the top surface. Figure 25 is a recording made to show this disbond. The stop-off material used was about one-fourth inch wide and 1/2 inch long.

A possible alternative is to use through-transmission between the front and back surfaces of the hub, but this also has severe limitations. This method does not give information on the depth of the flaw. Further, since the signal must travel about 12.5 inches, the ultrasonic energy may flow around a small flaw without giving a significant indication. The scarf joints occurring in the first several layers of the upper center section of the hub may be inspected with some degree of confidence if interface markers can be included to permit adjustment of the correct inspection angle. The markers could be located at the periphery of the hub and subsequently machined off.

There is also a small, but important, area in the hub that lies in the curved or fillet areas where it cannot be reached by straight-lined pulse-echo interrogation normal to any of the flat surfaces on the rotor hub. For these areas, another test method such as the delta technique may be employed.

An analogous condition exists in areas where high metal flow has occurred, causing gross deviation of the bond line from a plane parallel to the inspection surface. It is evident that a discontinuity of any finite length following the bond line in either of the areas adjacent to the fillets would not be normal to any inspection surface. Metal flow causes the interfaces to assume angles up to 30 degrees to the original boundary plane. Interface depths from the external surface have been observed which change by more than 1/4 inch. Detection sensitivity to a disbond on such an interface using conventional techniques is severely diminished, since it is strongly influenced by beam normality. However, where a local area of high flow is known to exist, several inspection techniques are potentially applicable. For example, an immersion transducer could scan a 90-degree arc and would probably detect gross discontinuities. The transducer assembly could also scan laterally along the laminate, giving an ultrasonic record.

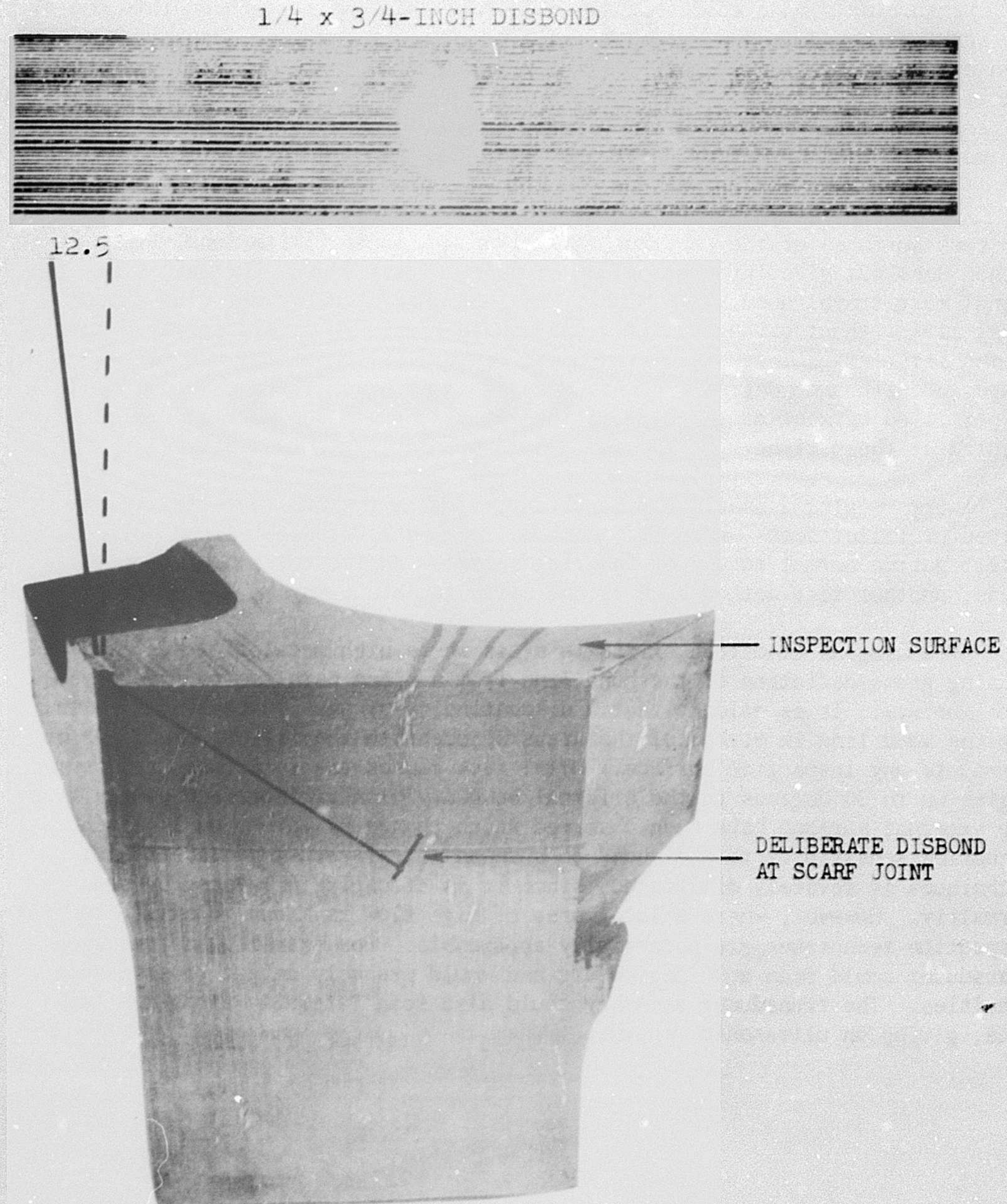


Figure 25. Ultrasonic C-Scan Record of Deliberate Disbond 1/4 x 3/4-Inch Located at Hub Scarf Joint; Transducer: 12 MHz, 3/8-Inch Diameter; 12.5-Degree Inspection Angle; Receiver Frequency: 2.25 MHz

RECOMMENDED INSPECTION PLAN

The following test procedure is based on results of the three rotor hub inspections and is intended for qualified ultrasonic operators. This inspection plan provides supplementary test data to be used in conjunction with standard aerospace ultrasonic inspection procedures (reference 4).

General Inspection Information

1. Specimen Preparation - The rotor hub as bonded has many sharp edges and ridges such as flash and die boundaries. Wherever possible, these protrusions should be smoothed for safety in handling the hub and to prevent them from causing false indications during inspection. The surfaces should be cleaned of any loose scale or other foreign matter.

2. Specimen Installation - The test specimen must be properly located under the scanning system so that the area to be inspected is covered by the recorder range. In most cases, it is desirable to level the front surface of the test part or make it parallel with the plane of the scanning fixture. The support fixture allows the hub to be leveled by means of three jackscrews. It can be rotated on rollers or wheels to bring each arm into position.

   In some cases, the recording gate position or gate width will be changed during a single record to compensate for sloping surfaces on the part. The rotor hub should be positioned so this variation is along the indexing axis of the scanning mechanism. In this way, the compensation can be made slowly and accurately. It is essential for the immersion tank to have sufficient depth. The specimen must be covered by enough water to allow the search unit to operate at the correct water path distance.

3. Transducer Selection - The transducer used to test a particular rotor hub area should be specifically selected. The beam characteristics for each search unit should be documented at each frequency to be used. The focal length and depth of focus should be determined as described for all transducers for focused units. For flat transducers, the near field distance (Y_0^+) should be known as well as the range on each side of that distance for which the sensitivity is constant within acceptable limits. This information should be measured rather than calculated.

   A procedure is outlined here to guide the operator in selection of a suitable search unit and water path for a test. There are limitations imposed by peculiarities in shape and size of the test specimen, attenuation of the material, etc, that cannot be included in a general treatment but will require judgment by the operator. As

an example, the narrow arm wall in which the metal path is several inches calls for use of a small diameter search unit to concentrate the energy in the narrow path, yet requires that the useful part of the beam must extend deep into the part. The long metal path length using a small unit would indicate the use of high frequency, yet this gives very high attenuation and limits the depth of penetration.

a. Step 1. Select the maximum depth within the metal (Max_m) and the minimum depth within the metal (Min_m) to be included in the gate for this record or test. The gate width (G) is the difference.

$$G = Max_m - Min_m$$

b. Step 2. The sensitivity of the search unit decreases as the depth is made greater than or less than the optimum value. For most search units, the response is usable from about two-thirds to 1-1/2 times the near-field distance. Actual limits will depend on the search unit and the allowable decrease in sensitivity for the particular test. A minimum near field distance in metal can be calculated.

$$G = Max_m - Min_m = 3/2\ Y_o^{+}{}_m - 2/3\ Y_o^{+}{}_m = 5/6\ Y_o^{+}{}_m$$

$$Y_o^{+}{}_{metal} = 6/5\ G$$

$$Y_o^{+}{}_{water} = 6/5G \bullet \frac{V_m}{V_w} \cong 5G$$

where V_m and V_w are the velocity of sound in metal and water, respectively.

c. Step 3. The near-field distance calculated in step 2 will not usually be the same as that of an available search unit. One must select a search unit having a near field equal to or greater than this minimum and having diameter and frequency characteristics suitable for the test.

d. Step 4. The near-field peak of the beam pattern should not fall at the center of the gated depth. The metal travel from front surface to the near-field peak can be determined by:

$$\text{metal travel} = Min_m + 1/3\ G$$

This dimension will properly position the beam when using minimum $Y_o^{+}{}_m$ and will insure that the gate is well within the linear region for search units with longer near-field distances.

e. Step 5. The water path distance from transducer to front surface will be the near-field distance of the search unit in water minus the water path equivalent of the metal travel.

$$\text{water path} = Y_o^{+}\ \text{actual} - (\text{metal travel}) \cdot \frac{V_{metal}}{V_{water}}$$

Sometimes the required water path is found to be too long for practical use or the required frequency is very high to attain the required beam length. In this case, compromise may be required. Water path can be reduced by narrowing the gate and making a greater number of records. Frequency can be lowered if a larger diameter search unit can be used.

Table V lists recommended test parameters which are in keeping with the prescribed selection methods.

TABLE V. RECOMMENDED TEST CONDITIONS

Area	Hub Position	Gated Depth	Search Unit Dia. (in.)	Search Unit Freq. (MHz)	Water Path (in.)	Rcvr. Freq. (MHz)	1st Std.	2nd Std.
Arm flange	Arm up	1/8 to 1/2	3/8	10	5	10	3 - 1/4 3-0025	3 - 1/2 3-0050
Arm wall	Arm up	1/2 to 1-3/4	3/8	10	2-1/2	10	3 - 5/8 3-0063	3 - 1-1/2 3-0150
Arm wall	Arms up	1-3/4 to 3-1/4	3/4	5	3	5	5 - 2 5-0200	5 - 3 5-0300
Arm wall	Arms up	3-1/4 to 5	3/4	10	7	10	5 - 3-3/4 5-0375	5 - 4-3/4 5-0475
Lug	Either	1/8 to 1-1/4	3/8	10	5-1/2	10	3 - 1/4 3-0025	3 - 1 3-0100
Lug	Either	1-1/4 to 2-1/2	3/8	10	4-3/8	10	3 - 1 3-0100	3 - 2-1/4 3-0225
Center	Either	1/8 to 2-1/4	3/4	5	8-1/2	5	3 - 1/4 3-0025	3 - 2 3-0200
Center	Either	2-1/4 to 4-1/2	3/4	5	1	5	5 - 2 5-0200	5 - 4-1/4 5-0425
Center	Either	4-1/2 to 7	1	5	8	5	8 - 4-3/4 8-0475	8 - 6-3/4 8-0675
Ramp	Arms down	1/8 to back	3/8	10	5-5/8	10	3 - 1/4 3-0025	3 - 3/4 3-0075
Center Flang	Arms down	1/8 to 1-1/4	3/8	10	5-1/2	10	3 - 1/4 3-0025	3 - 1-1/4 3-0125

4. Reference Standard Selection - Several types of comparison standards are used to evaluate untrasonic signals. A series of stainless steel balls having diameters from 1/16 inch to 1/2 inch have been found very useful in standardizing the sensitivity and linearity of the overall test system. They have also been used to determine beam characteristics of the search units. Special standards have been fabricated which more closely resemble the hub to be inspected than the commercial standards. In some cases, the standards are actually part of a rotor hub containing a flat-bottom hole or other signal target source.

5. Test System Alinement - The angular position of the transducer should be adjusted by means of an angular manipulator to aline the beam

perpendicular to the plane of the laminations. This plane is not always known nor fixed. A good approximation can usually be reached by maximizing the front surface or back surface signal, where these surfaces are parallel with the laminations. The standard blocks then should be positioned without changing the angular adjustment of the transducer. The blocks should be located within the scanning range of the recording system. The top of the standard blocks should be level with the front surface of the test specimen so the water path will be the same and the gate will span the same depth range. The angular position of the block also should be adjusted to maximize the signal from the flat bottom hole.

6. Test Sensitivity Adjustment - The reference standard selection is based on the standard giving a signal amplitude approximately equal to the largest allowable discontinuity at that depth. The receiver gain and attenuation controls should be adjusted to give about 80 percent of full-scale signal from the standard. The recording threshold should be set for 20 percent of full scale. Signal amplitudes 12 db below the critical level will be recorded. If background noise in the metal consistently shows on the recording, it may be advisable to increase the threshold level.

7. Test Recording - Make a C-scan recording of the specimen and the reference standards. All instrument settings and test parameters should be noted so the record can be properly interpreted; if necessary, the test can be repeated. A rubber stamp (figure 26) was prepared for marking each recording with the appropriate test data. In addition, the recording gate depth and width must be tabulated.

8. Data Analysis - Before the record is removed from the recorder or the position of the specimen is changed, the transducer should be brought into position over each recorded signal location. The source of the signal should be identified either as an actual material discontinuity or other phenomenon. Although the investigation of each recorded signal takes time, it can be accomplished most efficiently without changing the specimen or recording, and it is very difficult to make an absolute identification of a multiple echo or displaced gate sync after the part has been moved. If a recorded signal is found to be false, it should be identified on the record with a brief explanatory note.

   If a recorded signal is found to result from a discontinuity within the specimen, all available information about that signal should be noted on the record including the exact depth and plan position. The signal amplitude should be maximized by adjusting the angular position of the transducer to compensate for variation of target position. If the recorded spot is large, it may contain several high signal points,

RECORD NO.__________	SPECIMEN
DATE __________	SEARCH UNIT: FREQ ____ MHz, DIAM ____ IN
SENS. __________	FOCUS ____, S/N ____, TYPE ____
ATTEN. __________ DB	STD. BLOCK: SIZE ____, MATL ____
SIGN. AMPL. __________ %	SIG. AMPL. ____ %. S/N ________
RECORD LEVEL __________ %	INSTRUM: TYPE ____, S/N ____
DIAL __________	PLUG-INS: FG ____, RA ______
REJECT ____ PRF ____	COMMENT __________
DAMP ____ STC ____	__________
WATER PATH ______ IN.	__________
RCVR FREQ. ______ MHz	__________

Figure 26. Rubber Stamp Form for Test Condition Data

each point should be identified both in position and amplitude. The maximum signal amplitude also should be noted for each reference standard and for each recorded area.

Where feasible, the signal location should be marked on the surface of the specimen with a crayon or wax pencil. This location can be marked more permanently with a felt tipped Magic Marker pen after the specimen is dried.

Rotor Hub Components

The following inspection procedure is prepared for specific rotor hub component tests. Figure 27 shows the cross section of the rotor hub after it was sectioned with the circular lug at the end of the arm, the connecting sloped ramp or floor of the arm well, and the center section with the ring flange. In use on the helicopter, the arms are up and the ring flange is down. Figure 28 shows the cross section of an arm after the lug and part of the arm have been cut off. The arm ramp is at the top, and the arm walls are at either side and the arm flanges at the bottom.

A tabulation of test parameters and conditions used to inspect No. 2 and 3 hubs are given in appendix IV. These test conditions are not necessarily optimum but are intended to illustrate the evaluation conditions. Some compromises were not understood until after these tests were made, for example, in terms of optimum coupling. Since it was desirous to control the coupling, a decision was made to standardize all tests using immersion coupling rather than squirter or contact-type coupling system. However, the available immersion tank permitted water path lengths less than 4 inches. Therefore, all tests were made at 3-inch water path and a receiver frequency of 2.25 MHz, which gave a much shorter near field distance and also better penetration than would be possible using a higher frequency. The disadvantage is that the range of uniform detection sensitivity is also reduced. A longer water path used at a higher test frequency should give a slightly more accurate test. Table V lists test conditions that should give more uniform sensitivity.

The parts of the rotor hub can be grouped into four categories; flange areas, narrow walls, sloped ramps, and the deep center section. There are variations within each category, of course.

1. In the rotor hub, there are two types of flange to be considered. The arm flange is one of the least complicated areas on the hub and presents few problems from false signals or complex reflections. The major problem experienced with the arm flange has been due to surface conditions. Some areas show much greater attenuation at the surface than others and sensitivity to a discontinuity would be different in the two areas. In addition, there also is a ridge of

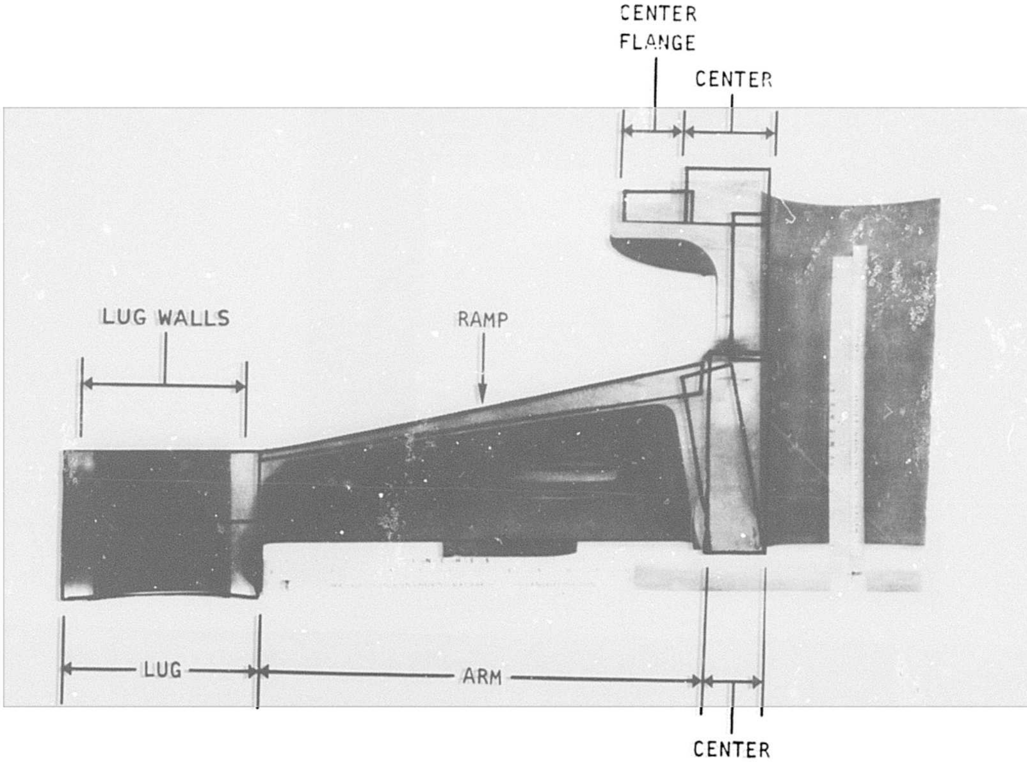


Figure 27. Cutaway View of Hub Showing Major Inspection Areas

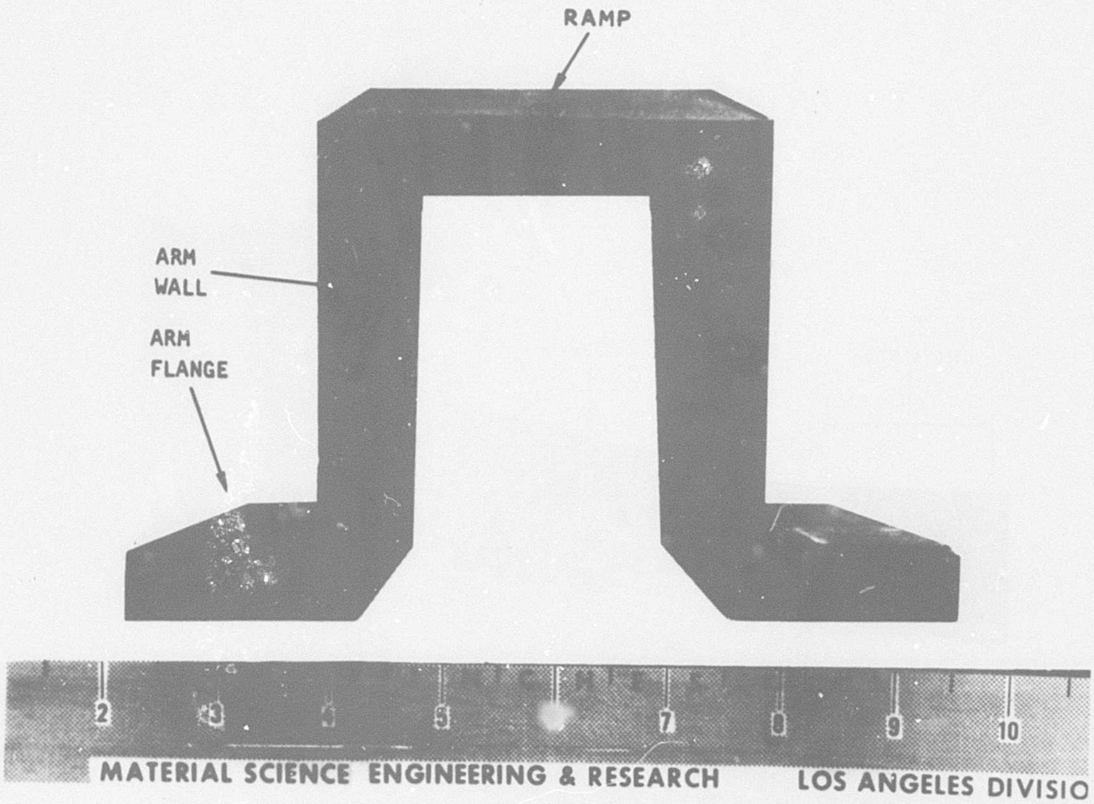


Figure 28. Cutaway View of Arm Showing Major Inspection Areas

flash along one edge of the flange that can cause false signals or shift the record gate if the video sync circuit is used.

The arm flange can be inspected using a flat or long focal length transducer. The length of the focal distance is important since a longer path gives a wider range of uniform sensitivity in the beam pattern. In addition, the lug extends about 2 inches above the plane of the flange, and to clear the lug, the scanning mechanism must hold the transducer at least 2 inches from the flange. To make the focal point or the near field distance fall about 1/2-inch below the surface of the metal, there will be at least 2 inches of water path plus the half inch of metal path which is equivalent to about 2 inches of water. The minimum equivalent water path is 4 inches. A transducer suitable for use with a longer water path is desirable to broaden the uniform sensitivity range. Since penetration is not a problem on the flange, a relatively high frequency can be used.

The gate should be set to fall as close as possible to the signals from the front and back surfaces. If the video signal is used to synchronize the gate, care must be exercised to insure that the ridge or flashing does not cause the gate to shift giving false indications. The titanium 6Al-4V standard blocks with 3/64-inch flat bottom holes at 1/4- and 1/2-inch metal travel distances are suitable for this test.

2. The ring flange or center flange is about 1-1/2 inches thick and contains three laminates. A flat transducer can cover this range satisfactorily with a suitable water path. The use of focused transducers could require performing the inspection at two or more depth ranges. The greatest source of difficulty in testing this area is the presence of a step of about 1 inch between the flange and the main center section. Multiple echoes from the center section near this step may fall within the gate, giving false indications. Careful observation of signals in this step area can be made by manually moving the scanning system to determine their cause. Standards having 3/64-inch flat-bottom holes at depths of 1/4 and 1-1/4 inches are suitable.

3. The rotor hub arm walls and lugs are classified as narrow walled areas. The arm walls are about 3/8-inch thick and the ultrasonic test beam is frequently of comparable or larger diameter. When a portion of the beam overlaps from the wall section to the adjacent flange area, there may be multiple reflections between front and back surfaces indicating a discontinuity deep within the wall. Or the energy may strike the fillet that joins the flange and the wall, reflect off the inner surface, and return to the search unit by the same path, also indicating a false discontinuity signal (figure 29).

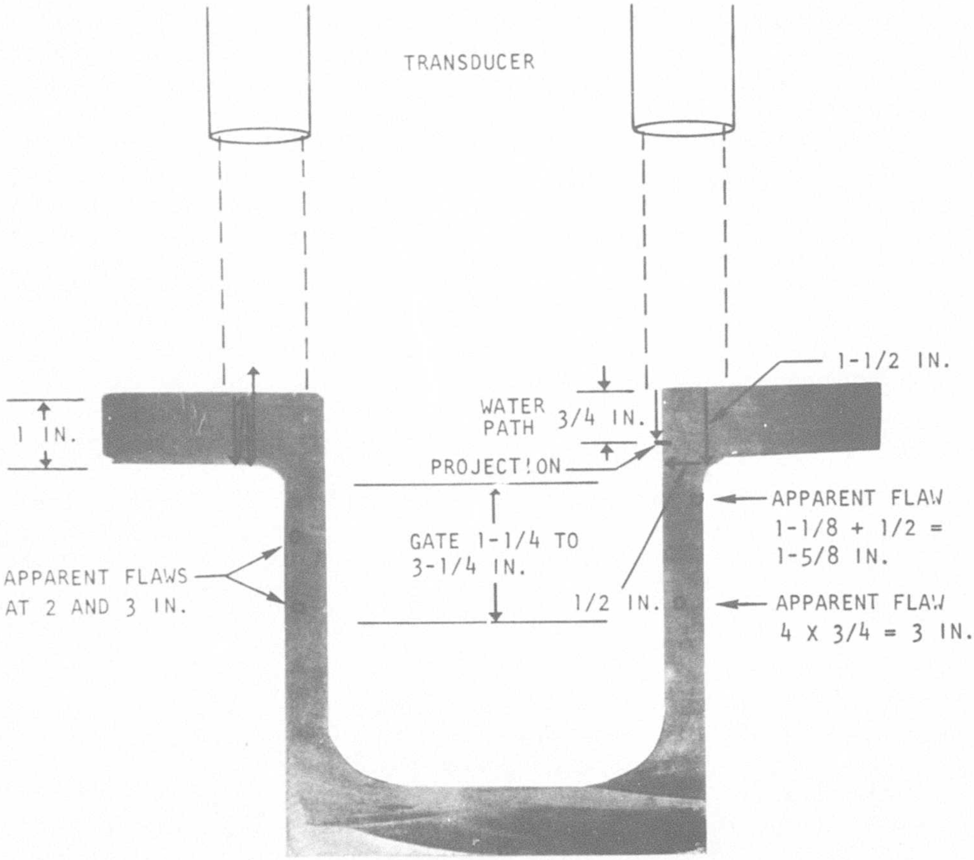


Figure 29. Three Sources of False Indication in Rotor Hub Arm Walls

In addition, consideration must be given to the rough surfaces on the inside wall surface. As mentioned in the discussion on geometry considerations, a protrusion or indentation can cause a water path echo that appears to be in the metal about four times the actual distance from the front surface. These water paths can be broken up by placing an ultrasonic absorbent or damping material along the wall edge just below the surface. Strips of zinc-chromate sealant material were successfully employed for this purpose. Irregularities on either the inside or outside surface of the wall can also send echoes through the metal that show up at the true depth.

The walls of the arm section have a thickness variation of about 3 inches at the lug area to 5 inches where the arm joins the center section. The testing can best be performed in three passes at increasing recording gate ranges. The upper 1/2-inch of the wall is normally included in the flange inspection. The first test recording can include the gate range from 1/2 to 1-3/4 inches; the second test can include depths from somewhat less than 1-3/4 inches to 3-1/4 inches; and the third pass should include the range of 3 inches to the lower edge of the pocket. The lower limit of the gate must be adjusted to include the entire wall area including the ramp. This means that the gate width must be changed either gradually or in steps to remain within the ramp area as the transducer is indexed along the length of the arm.

The 3/64-inch flat-bottom hole standards are recommended for depths up to 1-3/4 inches, either 3/64- or 5/64-inch standards from 1-3/4 to 3-1/4 inches, and the 5/64-inch standard beyond 3 inches.

4. The lugs were considered as narrow walled members measuring about 1 inch thick and about 5 inches deep. They can be tested from either side, giving a test depth of approximately 2-1/2 inches. The ultrasonic beam should have a small cross section and relatively uniform sensitivity over the 2-1/2 inch depth range for optimum sensitivity. Normally, two test scans are made at 1/8 to 1-1/4 inches, and 1-1/4 to 2-1/2 inches. Consideration should be given to the surface conditions and flashing. Roughness or impurities on the surface can cause large variations in signal amplitude and sensitivity. Like other parts of the rotor hub that have a ridge of flash along the edge, care must be exercised to insure that the record gate is properly adjusted to exclude the front surface echo.

The lug areas normally have flash on the inner and outer edges of the walls. As previously described, the ultrasonic beam may strike the flash on one edge, and be reflected through the water to the flash on the opposite wall. The acoustic energy may return through the same path, giving a signal at the equivalent of 4 inches of

metal travel, or may bounce directly from the second edge back to the transducer indicating a little more than 2 inches of metal travel. The signal indicated at 4 inches would not fall in a gate set for 3 inches, but the operator must exercise caution in evaluating any signals appearing at a depth of approximately 2 inches.

The lugs may also have rough areas on the wall sides. A reflection can occur from an irregularity either through the metal internal to the part, or externally through the water along the side, causing an apparent discontinuity indication.

Standard blocks with 3/64-inch-diameter holes at 1/4 and 2-1/4 inches of metal travel are suitable.

5. The floor or ramp of the arm is sloped with respect to the plane of the rotor hub (figure 22) and varies in thickness from the center area to the lugs. The plane of the front surface is about 12 degrees from that of the laminations. The acoustic beam must enter the front surface about 3 degrees from normal to strike the laminations perpendicular to the interfaces. The beam is thus about 9 degrees from perpendicular to the plane of the hub. This configuration requires a continuing adjustment of both the water path and record gate width. Inspection is performed with the arms down and the center ring up. The water path can be kept constant by tilting the hub to make the outer surface of the ramp parallel with the scanner or by adjusting the height of the search unit as the scanning mechanism is indexed along the length of the arm.

   The video sync circuit can be used to start the gate just after the front surface signal, and the width of the gate can be adjusted manually to end just before the back surface signal. This manual adjustment is difficult, and a small error in position can make the test ineffective. Automatic tracking would be rather complex, but a system could be devised which would servo-control both water path and gate width; recommendations are discussed later.

   Since the thickness of the ramp does not exceed about 1 inch, 3/64-inch-diameter standards at 1/4- and 3/4-inch depths are suitable.

6. The center section is the most complex part of the rotor hub to inspect, requiring testing to a depth of about 6-1/2 inches from opposite sides. Some of the fillet areas are difficult to record without including the back surface signal and can best be inspected by visual observation of the ultrasonic test instrument and manual operation of the scanning bridge. The fillet area where the arm joins the center section can only be inspected from the arm end and requires beam penetration of 7-1/2 inches. The beam must be

refracted into some locations by tilting the search unit relative to the entry surface, as shown in figure 30. When this is done, however, the beam is no longer normal to the lamination interfaces, and one must allow for a reduction in sensitivity.

The scarf joints are located in the center section. Figure 3 shows the makeup of the scarf joints before they are bonded. The surface is at an angle of 60 degrees to the plane of the hub before bonding and may flow somewhat during bonding. Measurements made on a sectioned specimen showed angles from 50 to 65 degrees after bonding. No method has been found to position the ultrasonic beam normal to the scarf joint interfaces except in the area near the surface of the rotor hub. Any discontinuity of appreciable size, however, can be detected by a transducer normal to the front surface.

The standards used for inspection of the center section will include 3/64-inch standards for areas near the surface and larger hole diameters such as the 5/64- and 8/64-inch standards with metal travel distances up to 7-1/2 inches. A special standard was fabricated with flat bottom holes drilled at several known angles relative to the surface to allow the operator to adjust the angle of the search unit for maximum response to a target that is not in the plane of the front surface, such as the scarf joints. The standard can be used to determine the approximate angle of the target by optimizing a transducer on a target or an interface that has flowed within a part.

The attenuation and noise characteristics of a test material can be different for various specimens from the same structure. As the metallurgical properties of the plate stock will vary from one production batch to another, it will not react uniformly to the time-temperature-flow conditions of a diffusion bonding process. Although the bond parameters are very closely controlled in the rotor hub, slight differences in grain structure can occur within one rotor hub and between a series of rotor hubs.

The signal amplitude from a discontinuity in a material is dependent on the attenuation of the metal through which the signal has traveled. Allowance can be made for any variations if the attenuation rate is known. The back surface echoes of a standard block and a portion of the hub can be compared to establish a relative value. As an example, the back surface echo can be measured for a standard block having an overall length of 5 inches and for the lugs on two rotor hubs, also about 5 inches long. If the signal level from the standard is 4 db higher than that from the first hub and 9 db greater than that from the second hub, it is obvious that the second hub has 5 db, or 1 db per inch, greater attenuation. This information can be used to correct the readings when testing specimens having higher than usual or lower than usual attenuation characteristics. It is necessary to eliminate other factors such as surface conditions for this comparison, of course. Surface conditions will appear as a fixed attenuation rather than in the form of db per inch.

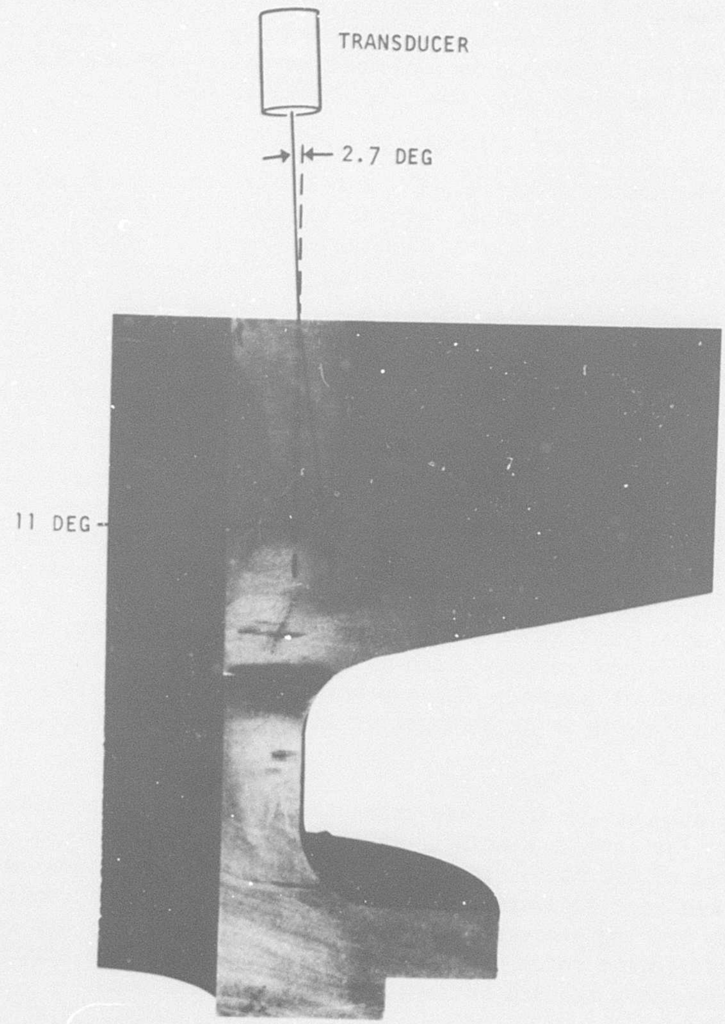


Figure 30. Mode Conversion Technique to Inspect Blind Area

DISCUSSION AND RECOMMENDATIONS

Ultrasonic inspections were performed on three H-53 helicopter rotor hubs and the test results indicated that no significant discontinuities were present. This conclusion is premised on two factors:

1. That acceptance criteria for a diffusion bonded structure of this size and type would allow a single discontinuous condition in the order of 1/8 inch diameter

2. That no indications were measured in the rotor hub inspections having an equivalent response greater than a 5/64-inch flat bottom hole standard.

The ultrasonic test system was capable of inspecting to this level, as indicated by test results that showed sufficient test sensitivity to detect minor differing metallurgical conditions approximately equivalent to the response from a 3/64-inch flat-bottom hole standard. Metallurgical examinations of selected rotor hub components where these signals occurred showed no discontinuities at either the diffusion bond interfaces or within the laminates, nor were any discontinuous conditions evidenced in the rotor hub as a result of the many sectioning and test coupon machining operations. Physical properties of the rotor hub material were investigated using destructive and nondestructive tests. Tensile and fatigue test results on specimens from representative areas of the rotor hub and at various orientations to the lamination plane compared favorably with those made on plate stock that contained no bonded interfaces. These data agreed with the results of the ultrasonic tests and indicated that diffusion bonding was effective.

For the most part, tests in this program were performed using relatively standard ultrasonic equipment and techniques, modified and adapted to the special requirements of the rotor hubs. However, the use of conventional ultrasonic test systems for complex structures such as the rotor hub is limited, and certain improvements are recommended. It should be noted that these limitations are not generally attributable to current equipment designs, but to the more extensive requirements of large complex structures. For example, the receiver-display characteristics of conventional ultrasonic instruments limit signal amplitude and time measurement accuracies in the order of 10 to 20 percent. For thinner, regularly shaped test materials, this accuracy is generally adequate. However, in thick sections such as the rotor hub with metal travel distances up to 7-1/2 and 12 inches, this measurement accuracy could cause gross errors in detection sensitivity and in determining discontinuity locations. Therefore, the digital voltmeter-depth gaging breadboard system was developed to extend signal measurement accuracies to the order of 1 to 2 percent.

Another potential problem area involves the correlation, collation, and analysis of a large quantity of inspection data and recordings. It is recommended that, as the transducer is indexed across the test specimen and the recording stylus is indexed across the recorder paper, a print wheel would identify every tenth or every hundredth scanning line. A counting mechanism could advance the print wheel giving a unique numerical identification to each location along the length of the record. A particular indication on the record could be permanently identified by noting its line number and distance from the edge of the record.

As the test progresses, an audio tape recorder could also be used to record comments on unusual or special conditions. The comment could include the numerical location of the phenomenon, such as a projection or rough area on the surface at location 2476. A photograph of the CRT showing an unusual reflection or echo could be included with the data to clarify an indication on the C-scan record. The photograph would be identified with the appropriate location and other pertinent data. An entire test or a whole group of tests could be serialized with each recorded signal having its own unique identification.

A rubber stamp along the edge of the recorder or elsewhere could provide a printed form for writing the location and information about test conditions at that signal area.

In diffusion bonded structures, the discontinuities tend to be two-dimensional in form, but their plane is often unknown. In many cases, they are not flat, but may curve or curl like a sheet of paper. An ultrasonic beam directed down into the test part might hit the discontinuity at an oblique angle so that the echo does not reflect back strongly into the search unit. Automation Industries have developed the "Delta technique" in which the reradiated energy is detected by two or more receiving search units mounted in particular position relative to the transmitter. The complex shape of the rotor hub makes it difficult to interpret results of the Delta measurements in terms of discontinuity size. An alternate method is recommended to compensate for this problem.

During the test work conducted on this program, it was often found that the amplitude of an echo could be increased appreciably by changing the angle at which the beam strikes the discontinuity. A beam entering the part normal to the surface usually is also approximately normal to the plane of the flaw, but it is only by adjustment of this angle that the signal is optimized. If the amplitude of the signal is low, it may be difficult to detect. Once detected, the signal can be optimized by hand, but this is time-consuming.

A test method which might provide a more complete inspection uses single transducer pulse-echo. The transducer would be rocked back and forth to give a wide range of angles of impingement on the target. As the search unit and scanning head move over the surface of the part and the angle of the head is varied with a nodding motion, there almost certainly will be a time when the beam is normal to the target and sensitivity will be high. This system has been called the NODDER (Noughten's Oscillating Defect Detection Enhancement Rocker). Two types of mechanical linkage have been devised to oscillate the transducer through the required arc (figure 31).

Since this system provides additional information about the angle and spatial location of the target, it also requires a more complex recording system to include all the information. Preliminary sketches have been made for an electronic circuit whereby the angle of the search unit and the depth of the echo are taken into account when plotting the target location. This information can be displayed on a CRT and photographed (figure 32). Alternate and better methods probably can be developed by more detailed study.

The transducer would be coupled to a sine potentiometer and oscillated through an arc, keeping the center of the beam at approximately the same entry point on the surface of the test part. The output voltage from the sine pot would be proportional to the sine of the angle to the normal that the beam makes within the part. For example, if the beam is normal to the front surface, the voltage will be zero, and if it is at an angle of 60 degrees to the front surface, the voltage will be:

$$V_{out} = V_{max} \sin 60° = V_{max} \cdot 0.866$$

Before the ultrasonic pulse reaches the front surface, the field effect transistor F_1 is open and F_2 is conductive, holding the operational amplifier output at zero. At the instant the front surface video pulse is received, the two switches reverse and F_1 becomes conductive and F_2 is nonconductive. The operational amplifier begins to integrate the voltage from the sine pot creating a linear sawtooth time base with slope proportional to the sine of the beam angle. Integrated signal amplitude then will be proportional to the length of time elapsed since the front surface echo, as well as being proportional to the sine of the angle. The voltage at time t will be:

$$V_t = K \cdot V_{max} \cdot \sin \phi \cdot t$$

where K is a scale factor constant, ϕ is the beam angle within the part, and t is the time that has elapsed since front surface echo.

Consider the case in figure 32, when the search unit is farthest to the right or clockwise, the beam in the material is 50 degrees from vertical or normal to the front surface, and two targets (identified as 2 and 1,

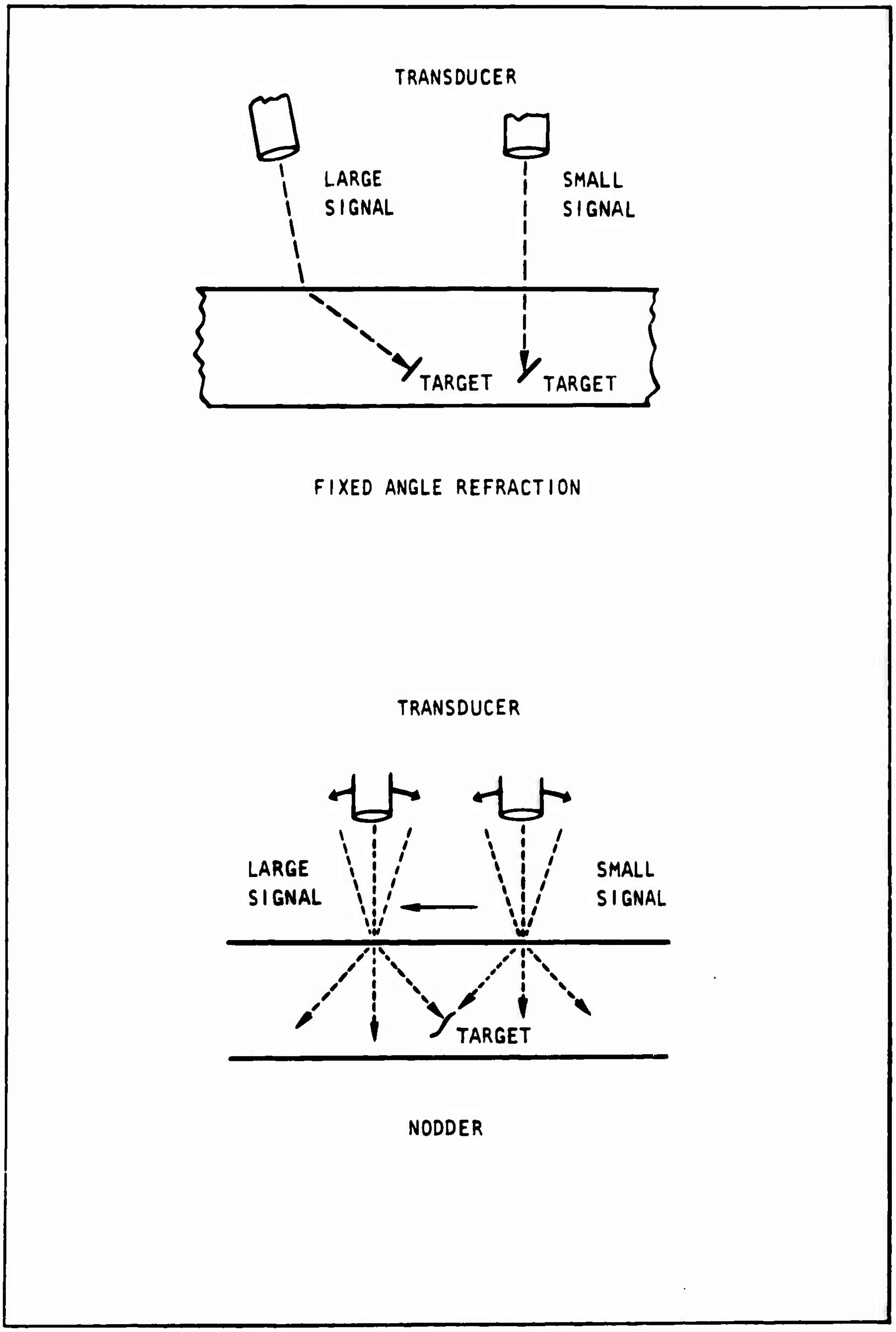


Figure 31. Methods of Normalizing on Target

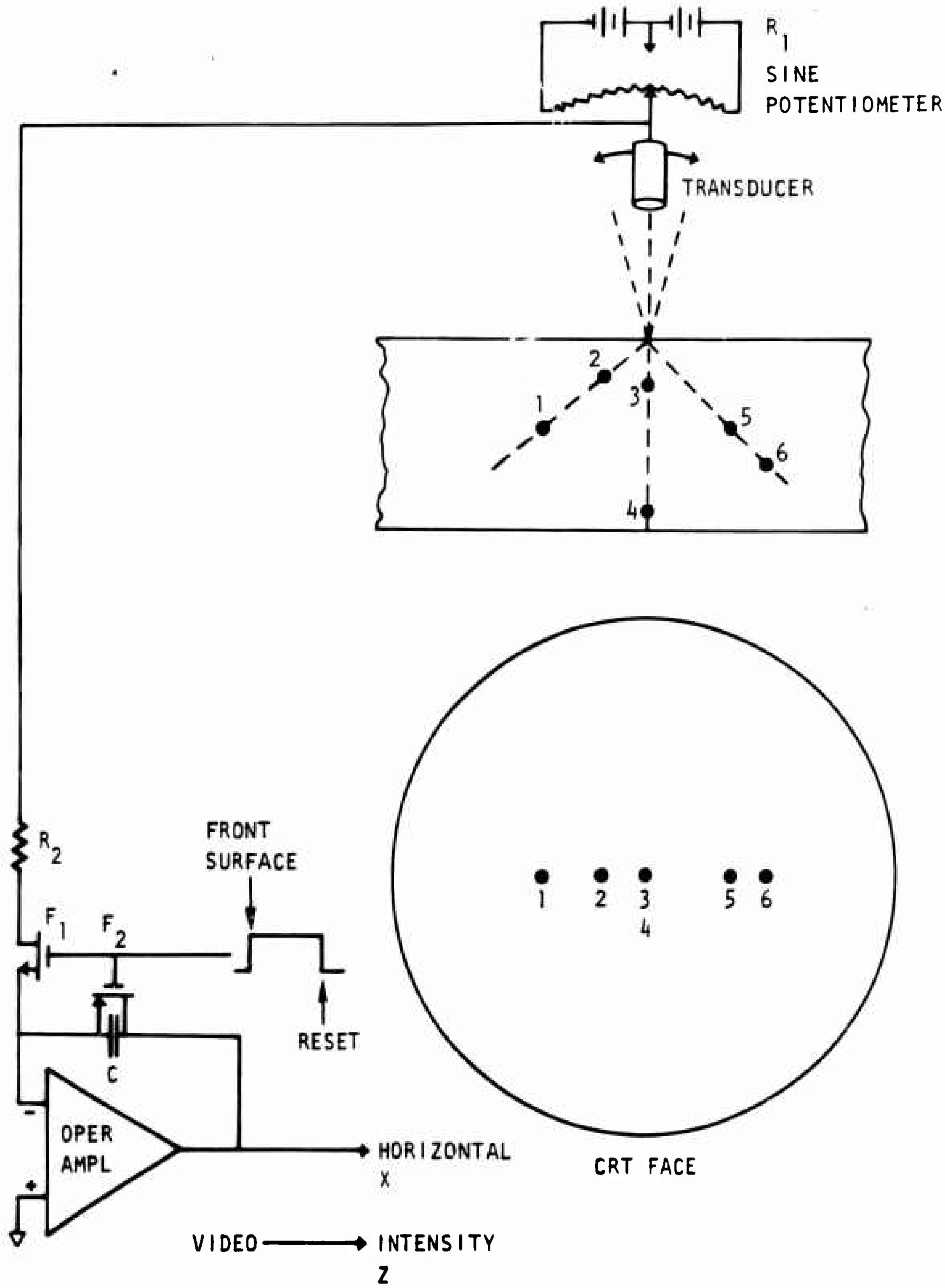


Figure 32. Data Display Technique for NODDER System

respectively) are encountered at 1 inch and 3 inches. The slope of the time base is proportional to the sine of 50 degrees. When the video pulse from target 2 reaches the search unit, the horizontal deflection will have moved from the center of the screen to the left one unit. The video is used to brighten the intensity of the CRT at that point. At the end of 3 inches of travel through the specimen, the time base has reached three times the amplitude, and the video pulse from target 1 will be three times as far from the center of the CRT. When the search unit is angled to the left, the beam will travel to the right and encounter targets 5 and 6, and the video signal will increase the intensity of the CRT to register bright indications at appropriate points. The intensity gives a relative measurement of the size of the target echo. Since targets 3 and 4 fall on the centerline where sin ϕ is zero, they both will be plotted at the center of the CRT.

If the CRT image is recorded on photographic paper that moves appropriately as the scanning head moves over the part, each target will appear on the paper in its true position as in a C-scan record.

After the ultrasonic pulse has traveled beyond the depth of interest in the part, the field effect switches can be reversed and used to reset the integrator before the next transmit pulse occurs. The input signal is shut off and capacitor C is discharged to be ready for the new measurement. The integration constant is determined by the capacitor C and the resistor R_1.

After a target signal has been detected, the amplitude should be maximized by changing the location of the transducer and its angular position relative to the front surface. This gives information about the true position and size of the target. These adjustments can be made by hand, but require alternately optimizing the angle, then optimizing the position, optimizing angle again and position, etc. A servo control on either or both of these adjustments could be helpful. The same motor used for the NODDER might position the transducer angle. The scanning and indexing motors could servo the scanning bridge. The same sensing system and the same servo amplifier could be used for both angle and scanning systems, alternately, or they might be used simultaneously through a multiplex arrangement.

Another inspection limitation occurs in testing areas such as the ramp of the rotor hub where the water path length changes as the transducer is indexed. Normally, the gate can be synchronized to the front surface signal so that the gate starts just below the surface. The actual water path is still changing, however, and there will be changes in attenuation. The location of the focal point or near field distance also changes drastically as the water path varies. The only way to maintain constant test conditions is to continuously raise and lower the transducer to keep the water path uniform.

Manual control was attempted by moving the search tube up or down during the test, or stopping the test frequently and correcting the water path in steps. Adjustment could be made smoothly during the test if the transducer

elevation were controllable by a motor drive. The motor could be controlled by the operator or could be servo-controlled.

The time delay between the transmit pulse and the front surface echo could be compared to the delay time corresponding to the desired water path distance. If the actual delay is longer than the selected value, the servo would move the transducer closer to the specimen. If the front surface signal comes too soon, distance would be increased. The ultrasonic beam may be off the specimen some of the time; hence, that comparison must be made while the transducer is over the area of interest, then disabled when no front surface echo exists or is not at the proper location.

The gate width also can be servo-controlled, but this may be somewhat more complex. In this case, the end of the gate might be compared in time with the video signal representing the back surface. If the end of the gate occurs just prior to the back surface echo by a selected period of time, perhaps 1 microsecond, the servo would be satisfied. If the comparison shows that this difference is less than 1 microsecond, the gate would be shortened to increase the time difference. If the time is too great, the gate would be lengthened to reduce the difference in time.

Several difficulties might be encountered with this type of servo control. If a large video signal occurs just before the back surface signal, the servo might jump or "home in" on this signal rather than the back surface and fail to record the discontinuity. Likewise, a multiple reflection or spurious signal might fall just before or just after the back surface signal, and cause erroneous readings. If the back surface does not register for some reason such as high attenuation, unfavorable reflection angle, or a large disbond that cuts off the beam, the servo would lengthen the gate in an attempt to find the back of the specimen.

Finally, in some tests, the signal-to-noise ratio is unfavorable where background noise is of a random nature. Various self-correlation and cross-correlation systems are capable of picking small signals out of a noise background many times larger. A boxcar integrator is a type of self-correlation system in which the same relative time slot is sampled and integrated for many successive ultrasonic echoes. The echo portion of the signal is repetitive and integrates to a very real value. Random noise is positive on one sample, negative on the next, and effectively averages or integrates to zero.

It should be realized that "metal noise" or background signals coming from gain or crystal boundaries are not random noise. They are the same on successive ultrasonic echoes, and are, in fact, a legitimate and bonafide signal that will be detected and recorded by the boxcar integrator and other self-correlation systems. Cross-correlation systems using two or more transducers can give signal-to-noise improvement even on metal noise. The signals from a target can be made to coincide and reinforce while the background signals are averaged.

Calibration Standards for Scarf Joints and High Metal Flow Areas

Several methods were evaluated for providing an ultrasonic standard for inspecting the scarf joints. These joints are so positioned that they are very difficult to inspect, and no simple standard gives a realistic basis for evaluation. The same factors apply to areas exhibiting high metal flow. Five possible methods for providing a standard were considered, comparing their respective advantages, disadvantages, and relative cost factors. Table VI summarizes the comparison with quantitative ratings assumed for the factors as they were evaluated.

- Method 1: Put deliberate disbonds into each hub as it is made. The disbonds would be placed at locations that are later machined off, near the surface on the sides of the hub. The material would be the same as that being inspected; it would receive similar processing and, therefore would exhibit identical ultrasonic characteristics. If there is metal flow or distortion of the interfaces, the disbonds would lie at approximately the same angle as any discontinuity. No external standard would be required, thus there would be no alinement or positioning problem for the standard. However, the intentional disbonds must be near the surface of the hub and not in an optimum position. Size, shape, and quality of each disbond standard would depend upon the care and control with which it is created, and characteristics in each hub might vary slightly. Additional planning and labor would be required to insert stopoff material as each rotor hub is fabricated. There would be little or no material cost, but this method might require as much as 16 hours on the first hubs and perhaps 4 hours in production quantities.

- Method 2: Drill flat bottom holes at the proper angle into the side of each rotor hub in areas later machined away. To inspect the deepest scarf joints, these holes would be drilled in the area of the star lamination. Again, the material and processing are the same as that being inspected. No external standard is required; there is no alinement or positioning problem for the standard; and hole size and surface flatness can be controlled quite accurately. Similarly, the intentional targets must be near the surface of the hub and not at an optimum position. The accuracy in size, angle, and hole location depend on the machinist's skill, and the additional labor required applies only to that particular rotor hub. However, in production, it should not take as long to drill holes as to add stopoff material as in method 1.

- Method 3: Use accepted ultrasonic reference blocks either as they are normally received or with suitable modification. It is known that manufacturers of commercial standard blocks use the best state-of-the-art methods and can be expected to produce more precise standards than those from a manufacturing line process. One set of standards can be used for many or perhaps all of the rotor hubs, without further expenditure, and all production units would be inspected to the same standard

TABLE VI. COMPARISON OF FACTORS AFFECTING SELECTION OF ULTRASONIC STANDARDS

Characteristic Evaluated	Stopoff in Each Test Part Method 1	Drilled Holes in Each Test Part Method 2	Commercial Standard Blocks Method 3	Drilled Holes in Existing Hub Method 4	Method 5
Similarity to rotor hub material 0, material not similar 10, material identical	10	10	3	7	8
Similarity to rotor hub contour 0, contour not similar 10, contour identical	10	10	2	8	9
Quality of discontinuity 0, poor uniformity, tubular cavity 10, planar, precise size and shape	5	3	3	3	9
Permissible locations 0, cannot place flaw in usable position 10, no limit on flaw location	2	2	3	7	9
Follows interface during metal flaw 0, has no relation to interface 10, follows laminate interface	7	0	0	0	8
Standard similar to natural flaw 0, signal not related to natural flaw 10, signal identical to natural flaw	7	4	5	5	5
Difficulty in Alining and Positioning 0, standard very difficult to position 10, standard automatically positions	10	10	5	5	5
Total Score	51	39	21	35	53

for good uniformity. But because the ordinary ultrasonic standard block is made with the flat bottom of the hole parallel with the entry surface, the conventional block would need to be machined to achieve the proper angles. Otherwise the block would have to be custom made. Conventional blocks have an entirely different shape and much smaller dimensions than a rotor hub. Methods other than simple, straight-line pulse echo would require very large blocks, preferably with special contours. Another handicap would be that the material presently used in standard blocks does not have the same characteristics as the rotor hub material. It is probable that a single set of standards would be less costly in the long run for large production lots than incorporating standards into each hub.

- Method 4: Use a segment of an existing rotor hub as the basis for building a standard. Part of the second half section might be used, with flat bottom holes drilled at the proper angle from the shoulder or fillet area. Since the metal, the shape, and the contours of the standard would be similar to the production items, Delta and other methods can be compared. Though the same standard would be used for inspecting all hubs, if an existing segment is used, we cannot introduce a flat or planar disbond. It will be necessary to use a drilled hole, which creates a tubular cavity behind the flat bottom, and this cavity might prevent use of NODDER or Delta methods. Also, ultrasonic characteristics of the material would not be identical to that of the inspected item; a method must be provided for positioning the standard and the test part; and drilled holes would not follow metal flow lines. Conversely, there would be no additional cost for material and a relatively small amount of labor would be required to cut a segment from the existing rotor hub and drill the proper holes.

- Method 5: Build a standard by bonding titanium blocks or plates into the desired configuration and inserting stop-off material to produce planar disbonds of proper size and location. This standard would be realistic, as the disbonds are two-dimensional and do not have cylindrical cavities behind them. Conventional delta methods could be used. Interfaces would assume the natural flow lines to be found in production rotor hubs. Disbonds could be placed at any location desired and would not be limited to the sides or fillet areas. The standard could be made in the same shape and size as an actual rotor hub section using some of the same dies, and would reproduce the same contours and ultrasonic paths. With material and processing similar to the production items, similar ultrasonic characteristics could be anticipated, and maximum uniformity would be achieved with one standard for all rotor hubs. Because the standard would be large and heavy, alinement of test part and standard for direct comparison would require extensive fixturing, although that would not be a major problem in the total system for a production run. Unfortunately, metal characteristics would be similar, but not identical, to the part being tested, as compared to methods 1

and 2. Initial cost of a standard with the shape and size of a rotor hub section would be high because of the need for special dies, but this cost would be easily amortized over production quantities, and still would be much less than incorporating holes or disbonds into each production hub.

PENETRANT TEST METHODS

Penetrant inspection has become a highly advanced inspection method at NR/LAD for detecting surface emergent discontinuities, particularly in diffusion bonded structures. The penetrant inspection process for diffusion bonded laminates (reference 5) is directly applicable to bonded titanium materials. On bonded surfaces, one frequently can observe the bond line between laminates, particularly when the surface has been ground or etched as an aid in determining metal flow conditions. However, this visual indication of a bond interface in most instances is not caused by a microdiscontinuous condition, but is due to differences in laminate texture (grain direction, etc). The latter condition was specifically noted in the lower center section of the rotor hub where laminates were alternately positioned during layup with respect to rolling direction. Penetrant inspection is applicable to determine discontinuous bond line characteristics, and emergent cracks and separations less than 0.0001 inch wide.

Therefore, penetrant inspection was performed on half of the second rotor hub to determine the presence of material or bond line discontinuities at laminate interfaces, fillet zones, inner diameter of the lugs and center hub, arm walls, and the juncture zones where the arms joined the center flange. The procedure used is described briefly in the following paragraphs, and specific processing precautions are noted for titanium bonded materials.

The rotor hub was cleaned. A plastic coating applied to the hub to protect the ground surfaces from fingerprints, etc, was removed using methyl ethyl ketone (MEK). The rotor hub was immersed for 5 minutes in a solution of 63-percent Baume-nictric acid and ammonium bifluoride. The ammonium concentration was controlled to give a 0.002- to 0.003-inch-per-hour titanium etch rate. This process is considered sufficient for cleaning without significant metal removal, and there is negligible hydrogen pickup. The rotor hub was dip- and spray-rinsed with deionized water and air-dried.

The NR penetrant solution Insta-Viz P5F-2.5 selected for the test is a high-sensitivity, fluorescent, and water-washable penetrant. The penetrant solution was applied with a spray gun to all rotor hub surfaces in approximately 3 minutes and allowed to air-dry for 3 minutes; then the excess penetrant was removed using an air-water spray (to prevent overwashing, a minimum spray force was used). Further penetrant excess was locally removed with lint-free cloth and MEK solvent while observing the surface under blacklight

illumination. The rotor hub surface was then air-dried for a minimum of 2 minutes. The total application and verification time was approximately 12 minutes. Observation of penetrant indications may be made for periods up to several days after application.

The rotor hub surfaces were viewed in a darkened room or enclosure using a blacklight illumination source providing at least 125-foot-candle intensity level.

In general, no significant penetrant indications were observed on either the as-bonded or ground rotor hub surfaces. Inspection was performed visually with a 10X optical magnifier. Penetrant indications were noted on the rotor hub arm walls where the metal flow did not completely obliterate the laminate lines. The internal bond quality in these areas was satisfactory, as shown by the metallographic and mechanical property tests.

Penetrant tests were also made on the arm walls of the third rotor hub where the metal had not flowed sufficiently to completely fill the die. There was no evidence that the separation between laminations extended beyond the depth that was observed visually.

Penetrant tests were performed on two segments cut from the first rotor hub containing deliberate disbonds. A thin titanium foil coated with yttrium oxide had been included between two laminates before bonding. It was shown through metallographic study that the yttrium oxide provided a completely inert disbond mechanism without otherwise affecting the metallurgical properties of the material. The penetrant test of a sectioned disbond showed a narrow crevice was created by the yttrium oxide. Dye introduced at one end of the disbond progressed along the crevice due to capillary action. There was relatively little bleeding or emergent dye after the area had been flushed with MEK and allowed to dry, indicating that the crevice was very narrow.

RADIOGRAPHIC TEST METHODS

A total of 18 radiographic exposures were made on representative sections of the rotor hub including lug, arm, and center sections. The radiographic films clearly showed the yttrium-oxide disbonds but no other significant material detail. The X-ray radiographic inspection of thick titanium material using conventional equipment, techniques, and exposure conditions was not considered promising due to the low energy levels available; no further radiographic effort is planned. Some improvement could be anticipated using betatron-type radiographic equipment.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

Three H-53 helicopter rotor hubs, fabricated by diffusion bonding processes, were nondestructivity evaluated using ultrasonic, penetrant, radiographic, and visual test methods. The nondestructive test (NDT) results showed no significant discontinuities that could affect the performance of the rotor hubs in service. The NDT results were correlated with metallurgical examinations and mechanical property tests. The metallurgical examinations confirmed that the ultrasonic test sensitivity was sufficient to detect minor grain structure variations equivalent to the response from a 3/64-inch flat bottom hole standard in rotor hub metal travel distance of 7 inches. In addition, the tensile and fatigue properties of rotor hub specimens including the 1/2-inch laminate interface and scarf joint interfaces showed no discontinuities, and strength levels approximated the properties of the plate stock material. Ultrasonics was the primary NDT method evaluated, and significant progress is reported in the utilization of ultrasonic techniques for complex diffusion bonded structures. The most important factor gained from the ultrasonic studies is the need for systematic evaluation and understanding of the material effects on the acoustic beam propagation characteristics. The rotor hub exemplifies a wide range of shape and material variations that can be misjudged and, either independently or in combination, can invalidate the test investigations. These variations are discussed in general terms and apply to most complex structures. Detailed descriptions of these variables in terms of the specific rotor hub components and test considerations are included. This information, in conjunction with the recommended calibration standards and procedures, should enable a qualified ultrasonic inspector to perform a competent evaluation of a rotor hub.

The applicability of penetrant and other visual techniques for surface emergent discontinuities was established and should be employed with ultrasonic techniques for a complete nondestructive evaluation of the rotor hub. The radiographic evaluation confirmed the applicability of the method for the detection of gross differences in material densities such as tungsten inclusions in titanium sections but negligible applicability for air or gas type discontinuities. Radiographic techniques did show an unanticipated applicability for the detection of the yttrium oxide stopoff material used for deliberate disbond standards. In this regard, radiographic techniques could be used to cross-check the ultrasonic detection and location of deliberately introduced disbond standards in areas of the rotor hub subsequently removed during machining.

It was anticipated at the outset of this program that more effort would be directed toward evaluating a wide range of discontinuous type conditions and locations. However, this was not possible due to the uniformity of the

rotor hub properties. Future studies should be directed toward the NDT characterization of a range of types and sizes of discontinuities using a series of specially designed diffusion bonded specimens. Such a program should be directed toward not only evaluating and developing NDT methods, but also include a correlation with a range of mechanical properties selected for specific stress and load rate conditions. This approach will also lead to the definition of realistic diffusion bond acceptance criteria. In summary, the recommended approach is outlined as follows:

1. Knowledge of the NDT principles and capabilities

2. Understanding of the various types of defects and their effect relative to various diffusion bonded materials and test part shapes

3. Analysis of the NDT methods as related to the specific interactions of defect location, shape and geometry, and the material metallurgy and shape

4. Characterization of the defect type and structure as a function of service stress and environmental factors

5. Correlation of all data into an analysis that includes the NDT factors, and defect/material shape, geometry, and location interactions

Detailed recommendations for specific system improvements are listed in the section on ultrasonic methods. Briefly, these recommendations include improved NDT data recording and analysis techniques, a unique ultrasonic "nodding" transducer system for inspecting diffusion bond areas where discontinuities are not normal to the inspection surface, a servo-controlled transducer manipulator system for automatic compensation for changing water path, and automatically controlled recorder gate width and location system, and an automatic digital signal depth and amplitude measuring system.

APPENDIX I

CIRCUIT DIAGRAMS FOR THE ULTRASONIC DIGITAL DEPTH GAGE

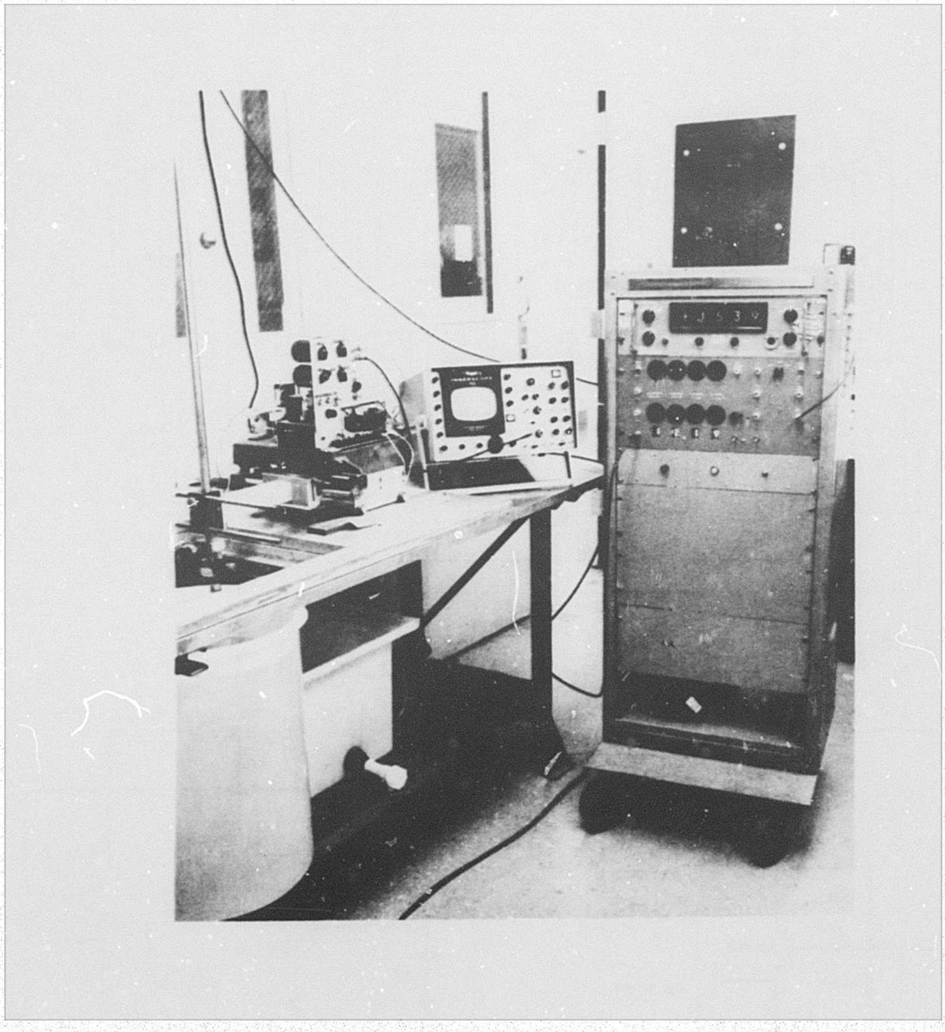


Figure 33 Test System With Digital Amplitude and Digital Depth Readout

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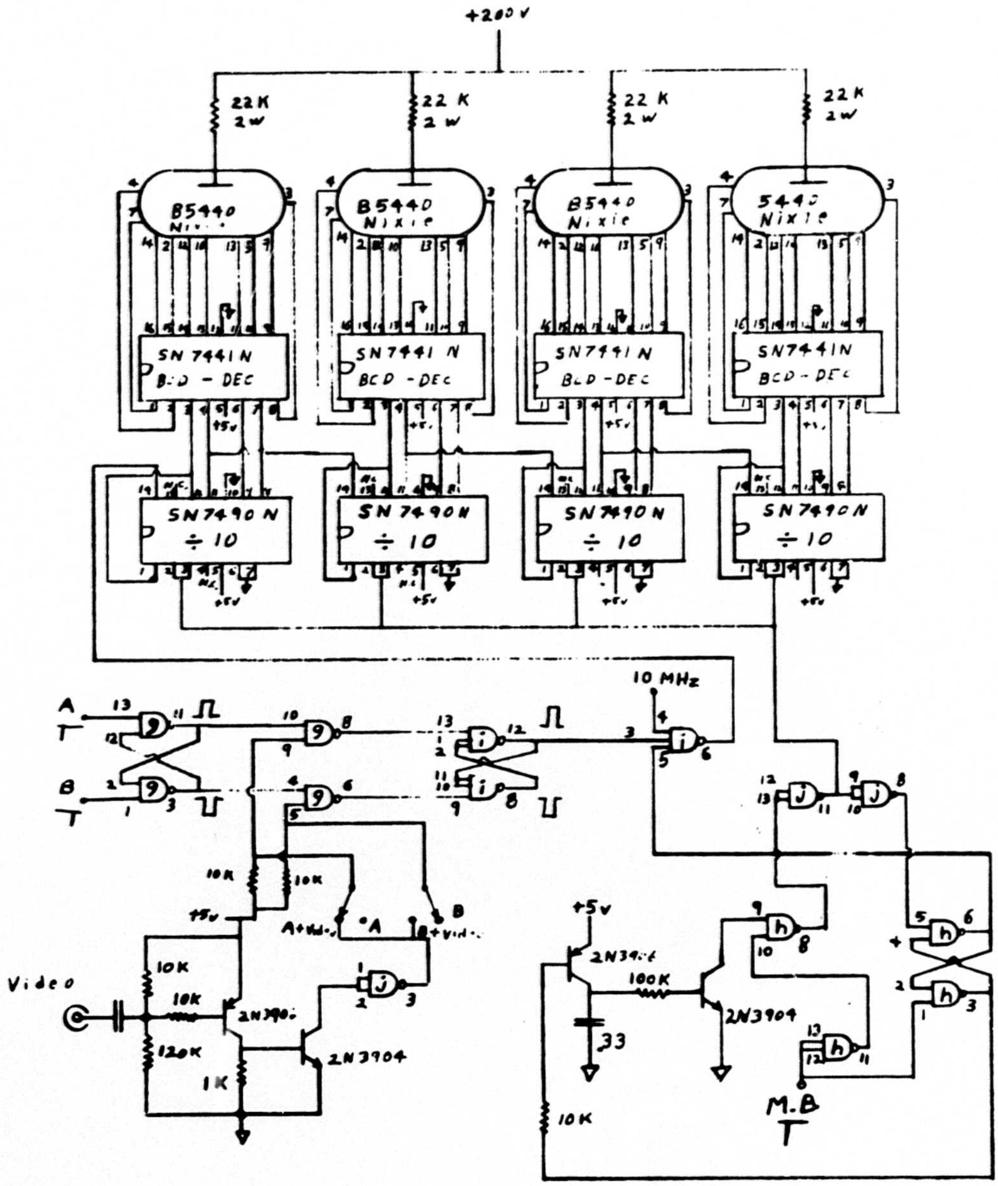

Figure 34 Digital Depth Gage Circuit Diagram - Time Base

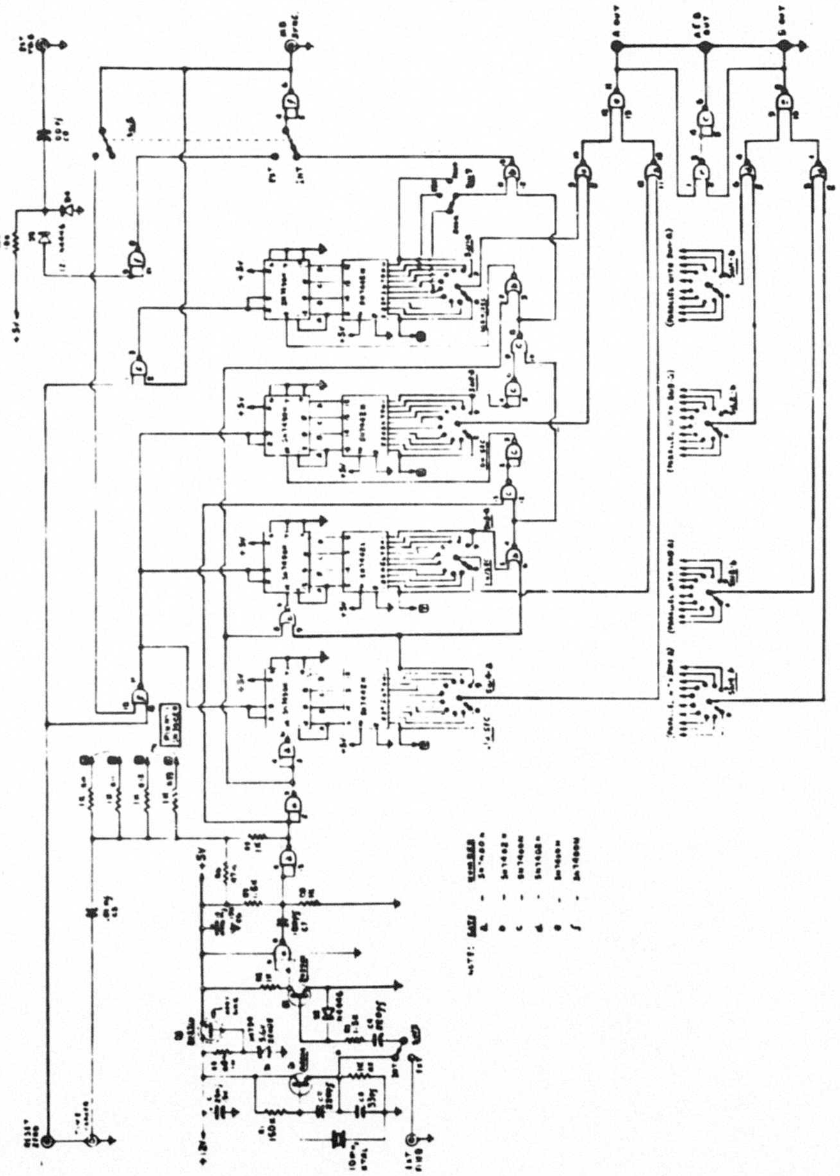

Figure 35 Digital Depth Gage - Circuit Diagram

APPENDIX II

DRAWINGS FOR THE ROTOR HUB POSITIONER FOR ULTRASONIC TESTING

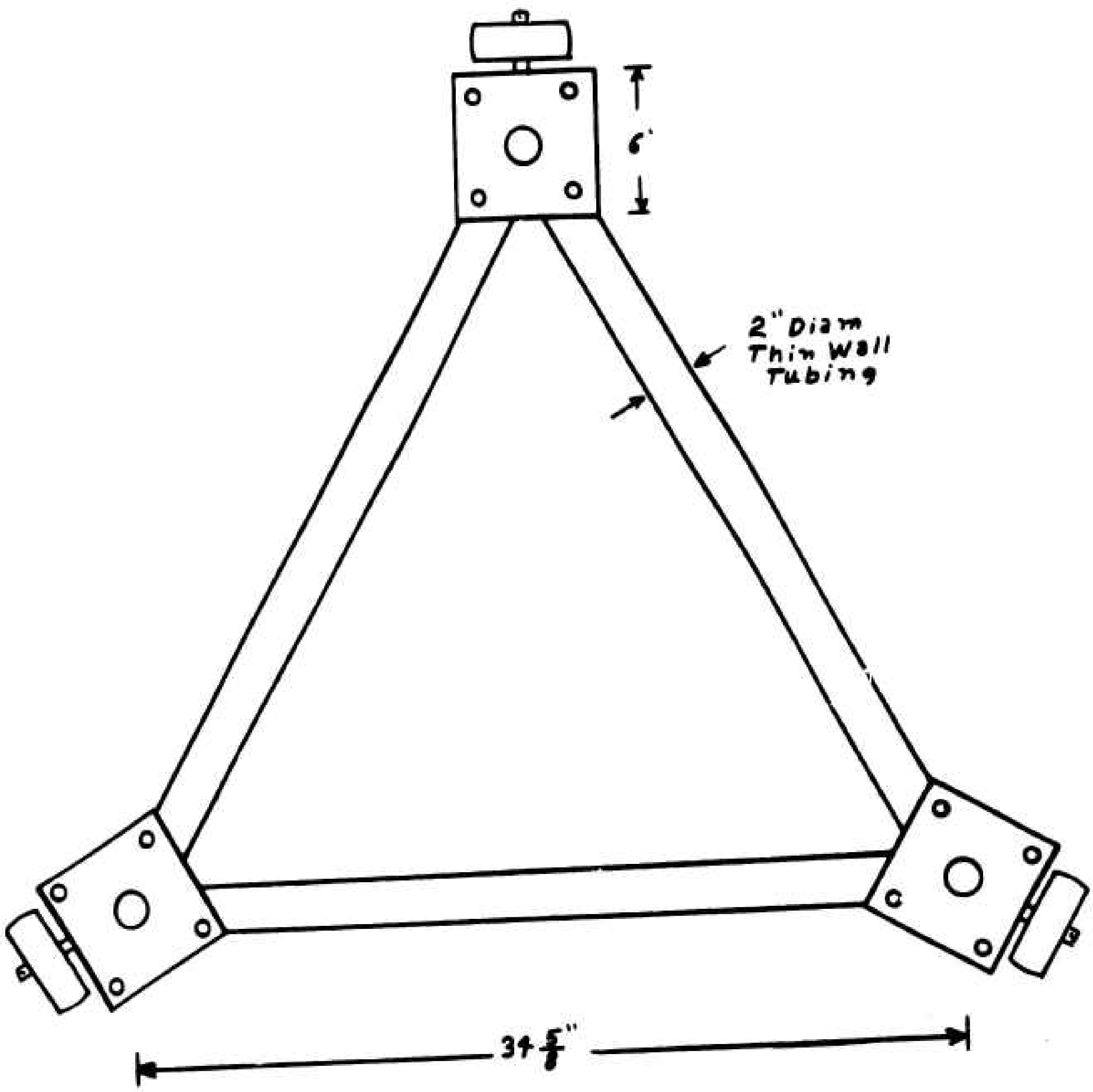

Figure 36 Ultrasonic Hub Positioner Drawing - Assembly

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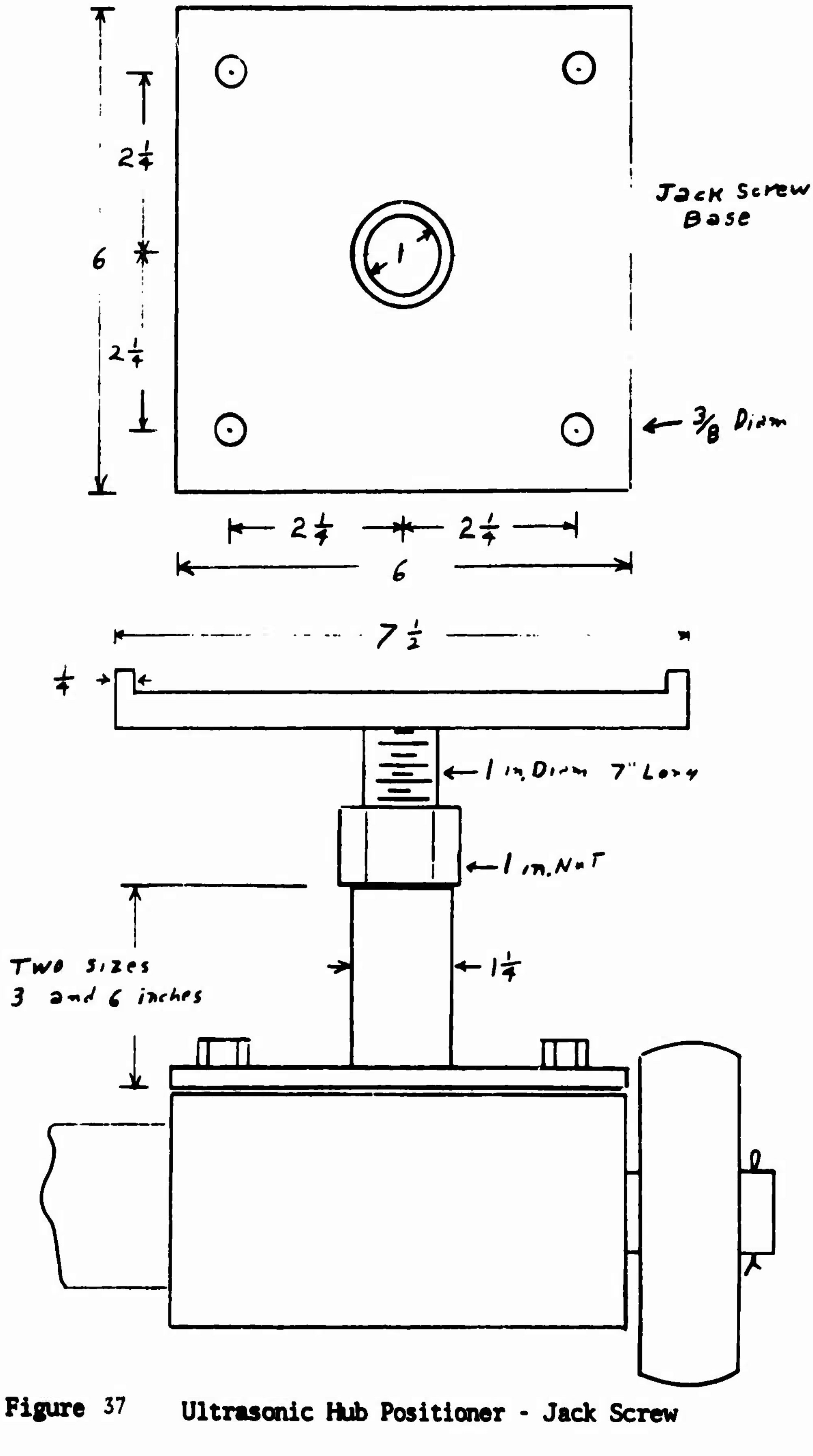

Figure 37 **Ultrasonic Hub Positioner - Jack Screw**

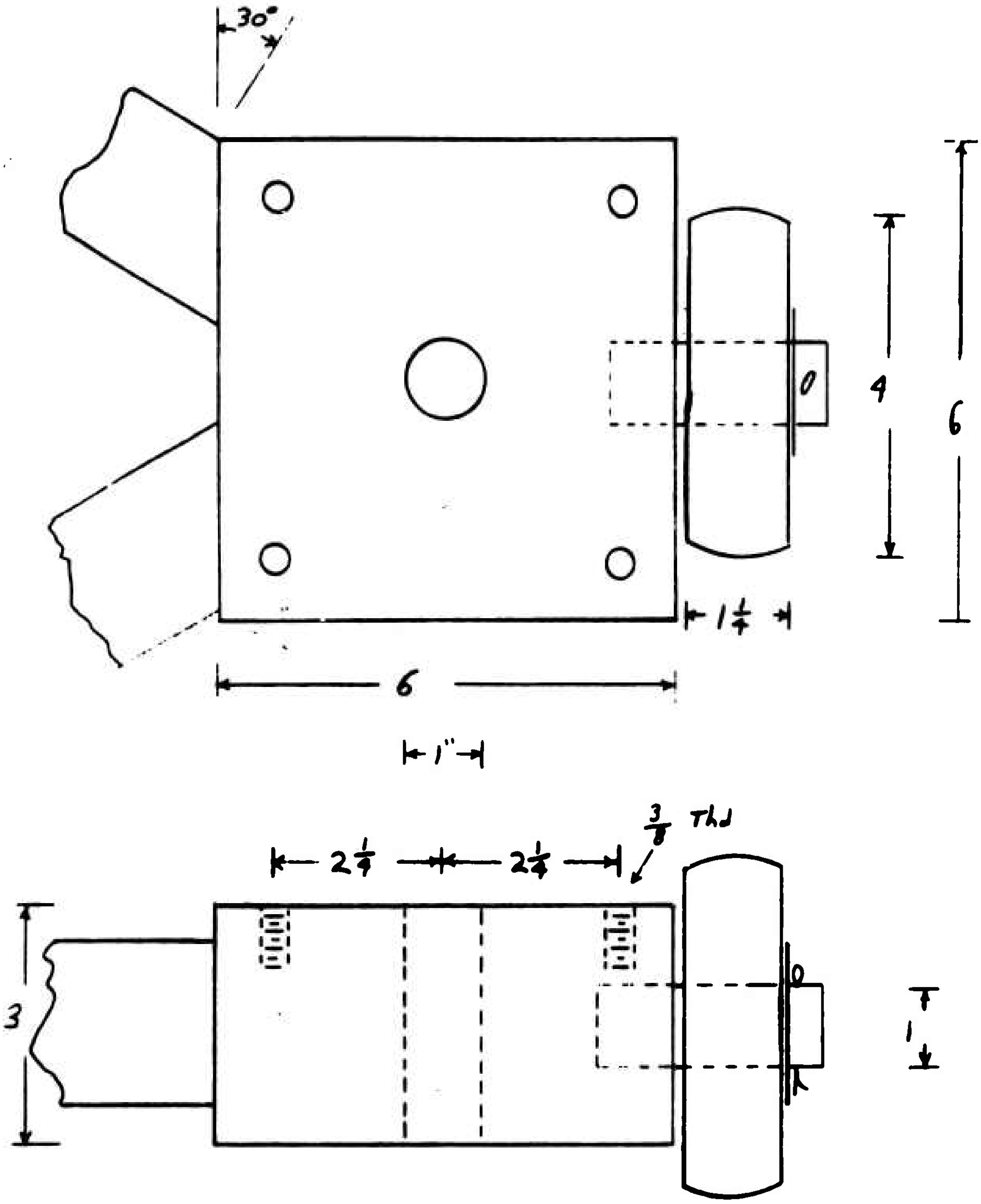

Figure 38 Ultrasonic Hub Positioner - Wheel Assembly

APPENDIX III

PHOTOGRAPHS AND DRAWINGS OF THE ULTRASONIC REFERENCE STANDARDS

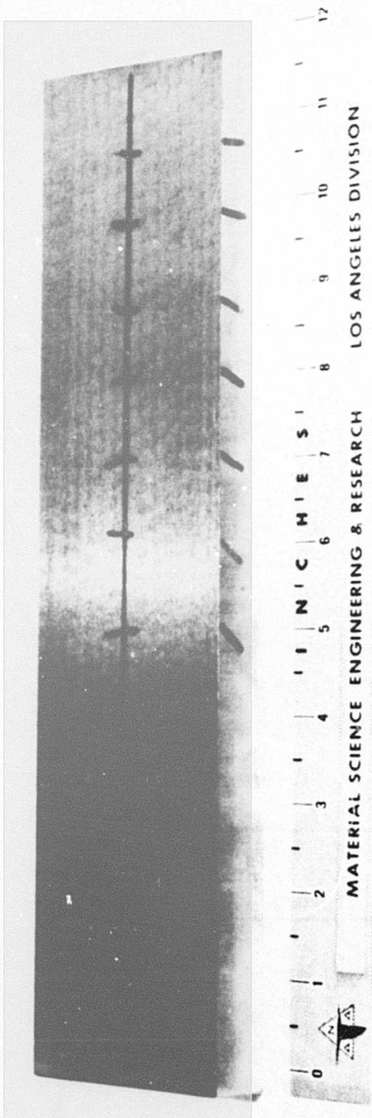

Figure 39 Photograph of Scarf Joint Standard

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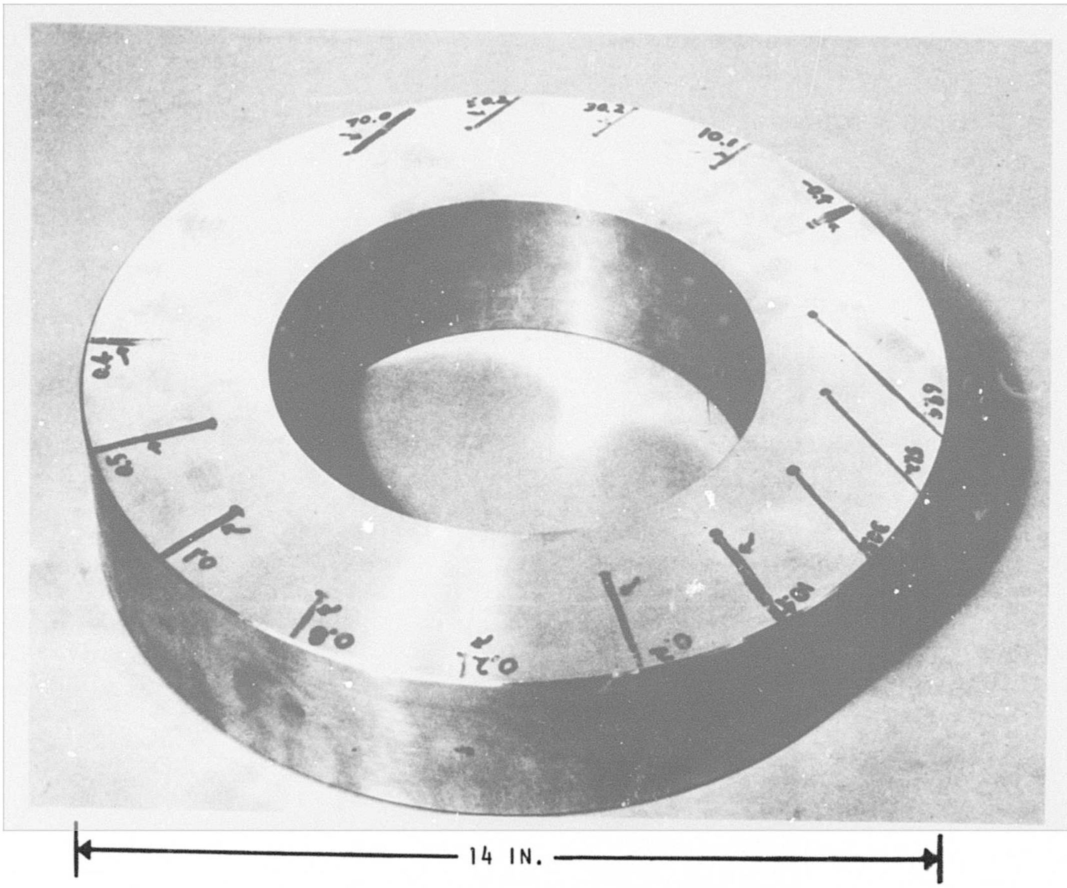


Flat Bottom Hole No.	Angle To Ring Radius Degrees	Distance From I.D. Inches
1	0.4 CW	0.59
2	0.5 CW	1.02
3	0.1 CW	1.57
4	0.8 CW	2.04
5	0.2 CW	2.56
6	0.2 CW	1.05
7	10.4 CW	1.05
8	30.5 CW	1.06
9	51.2 CW	1.06
10	69.9 CW	1.03
11	0.4 CCW	2.06
12	10.1 CW	2.06
13	30.2 CW	2.06
14	50.2 CW	2.06
15	70.0 CW	2.03

Figure 40 Photograph of Rotor Hub Ring Standard

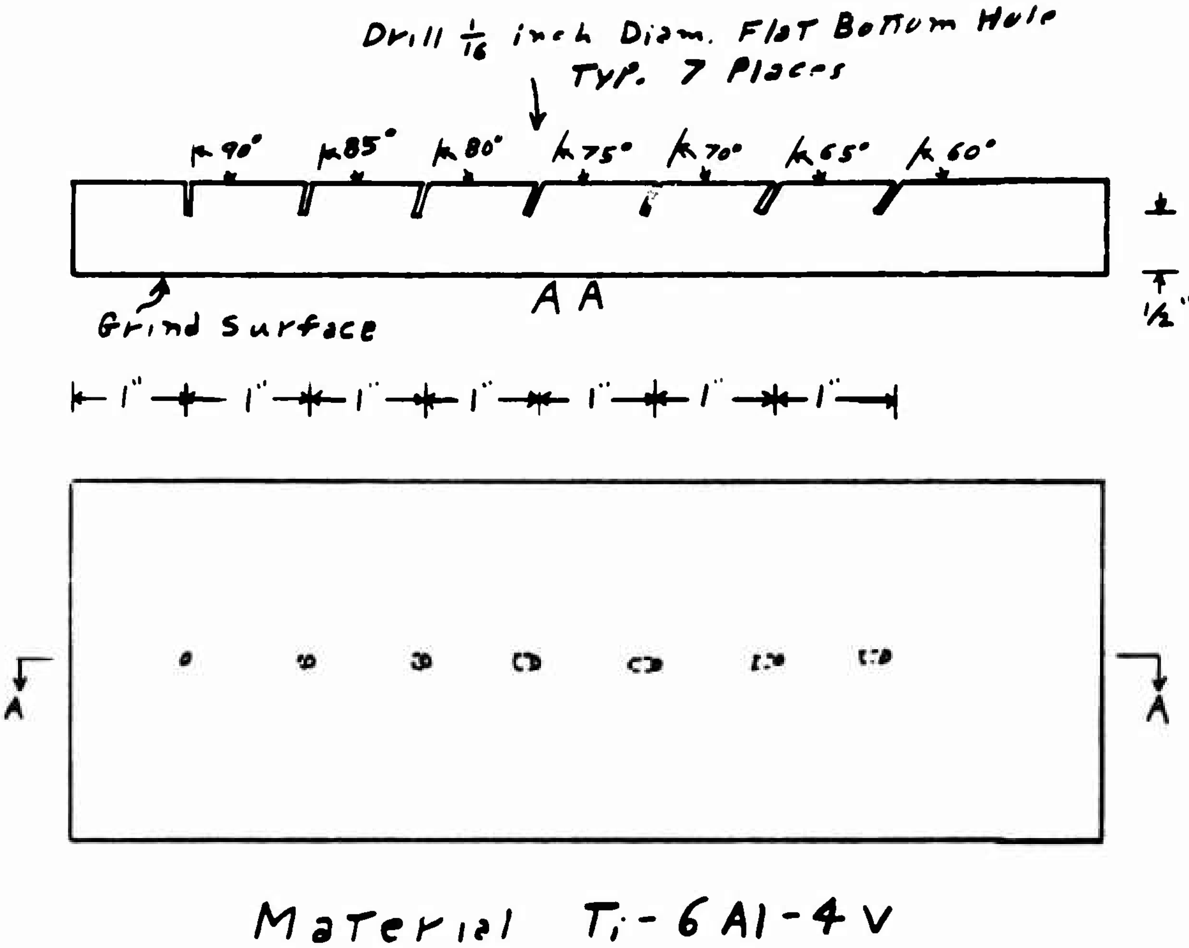


Figure 41 **Drawing of the Scarf Joint Standard**

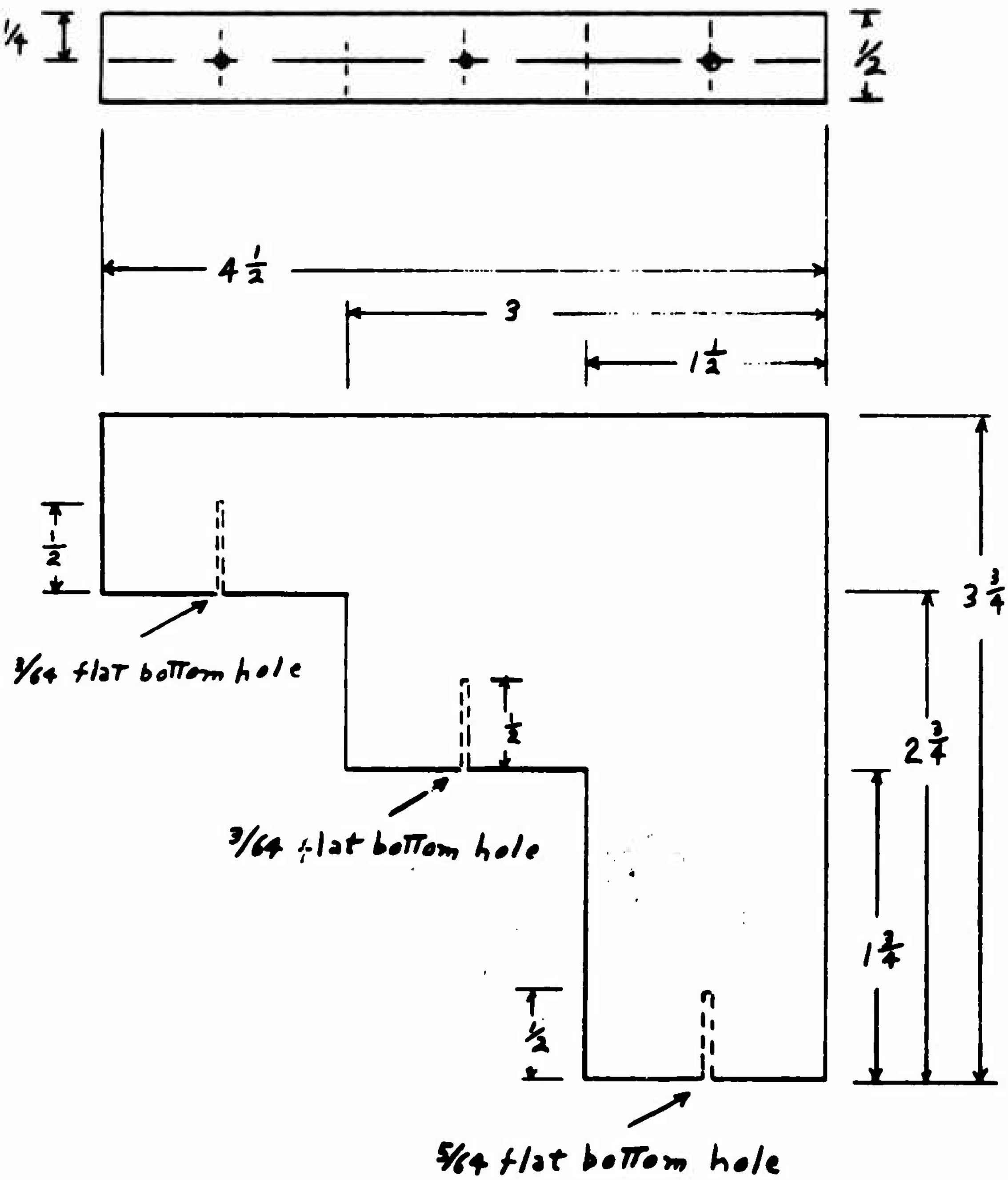


Figure 42 Drawing of the Rotor Hub Arm Wall Standard

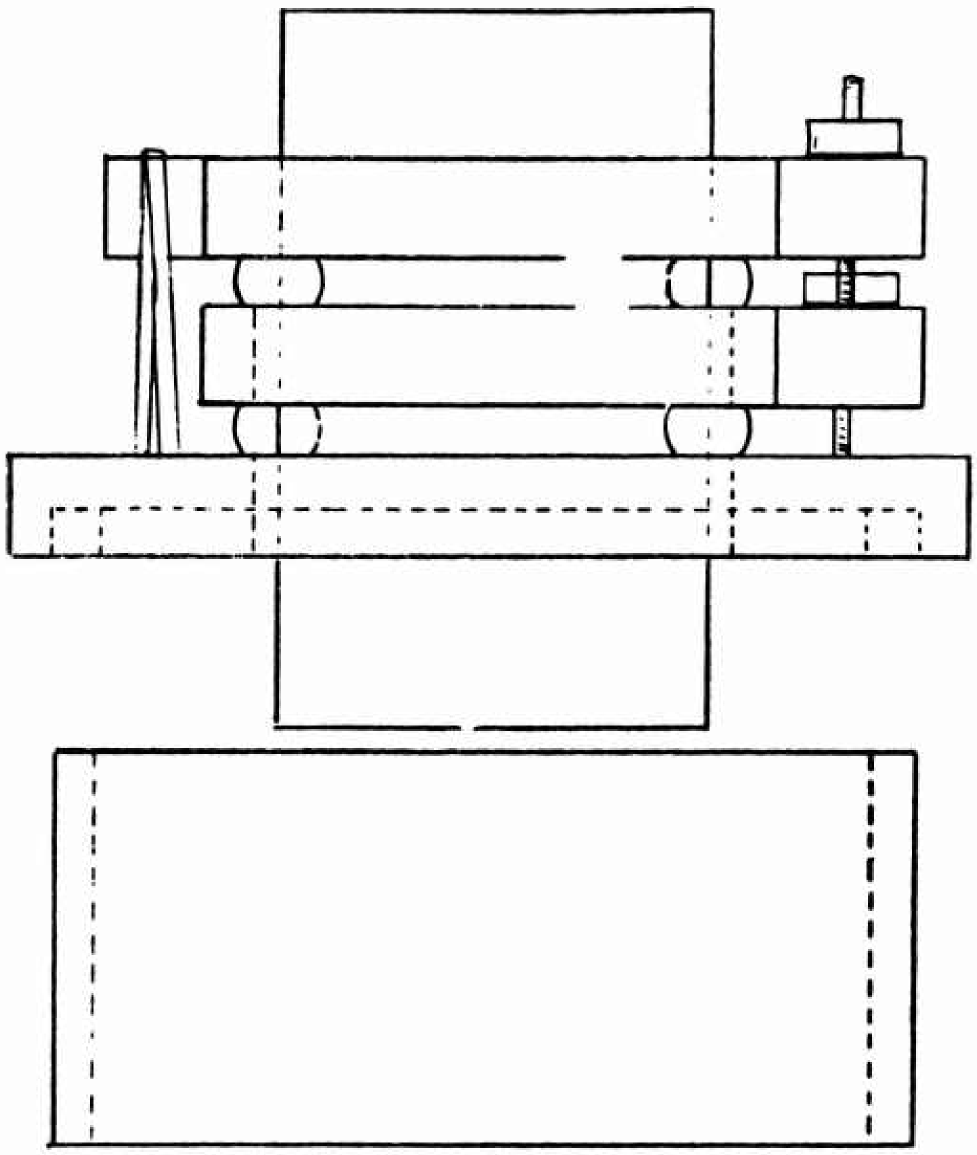


Figure 13 Calibration Fixture - Assembly Drawing

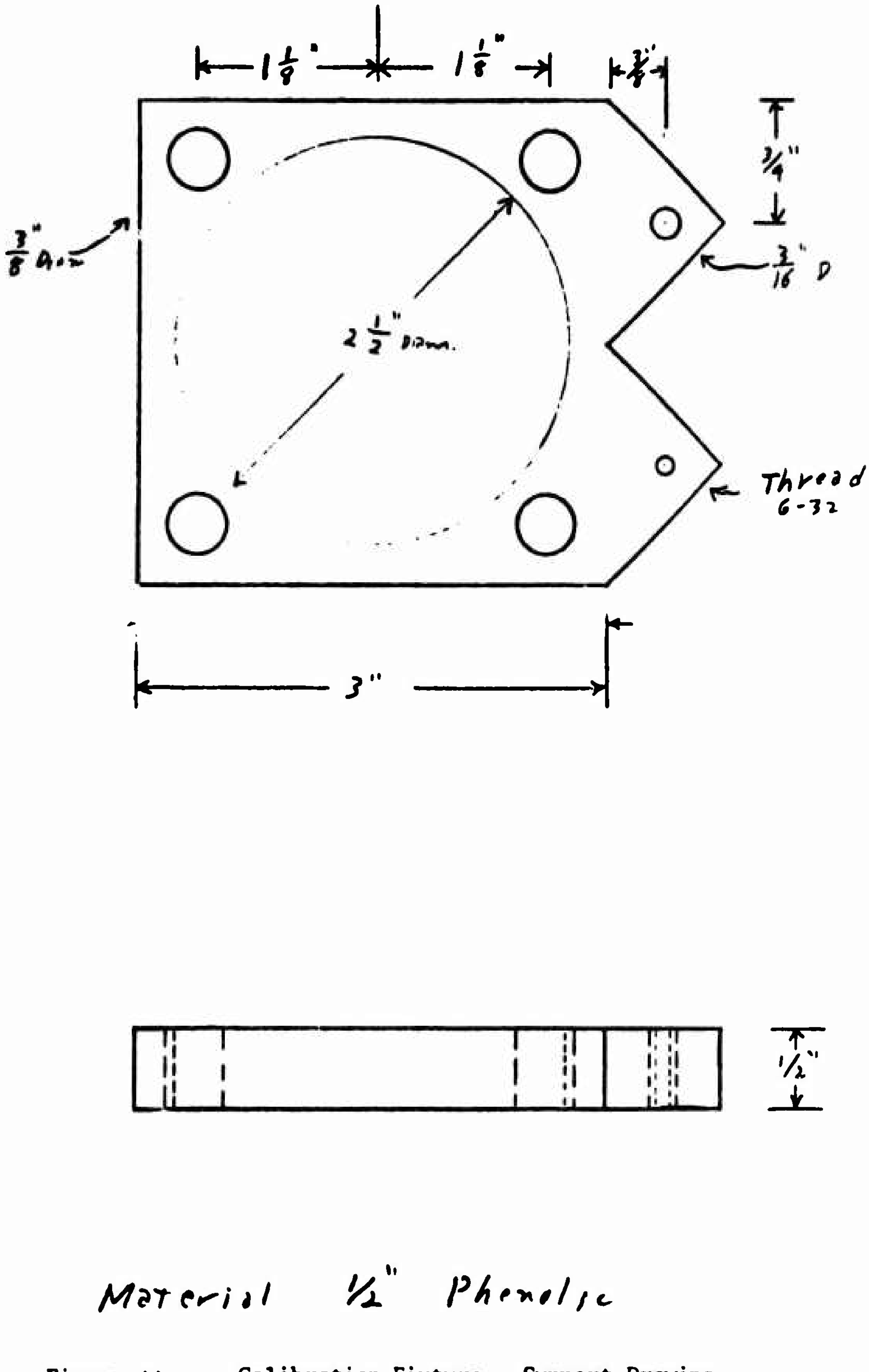


Figure 4.1 Calibration Fixture - Support Drawing

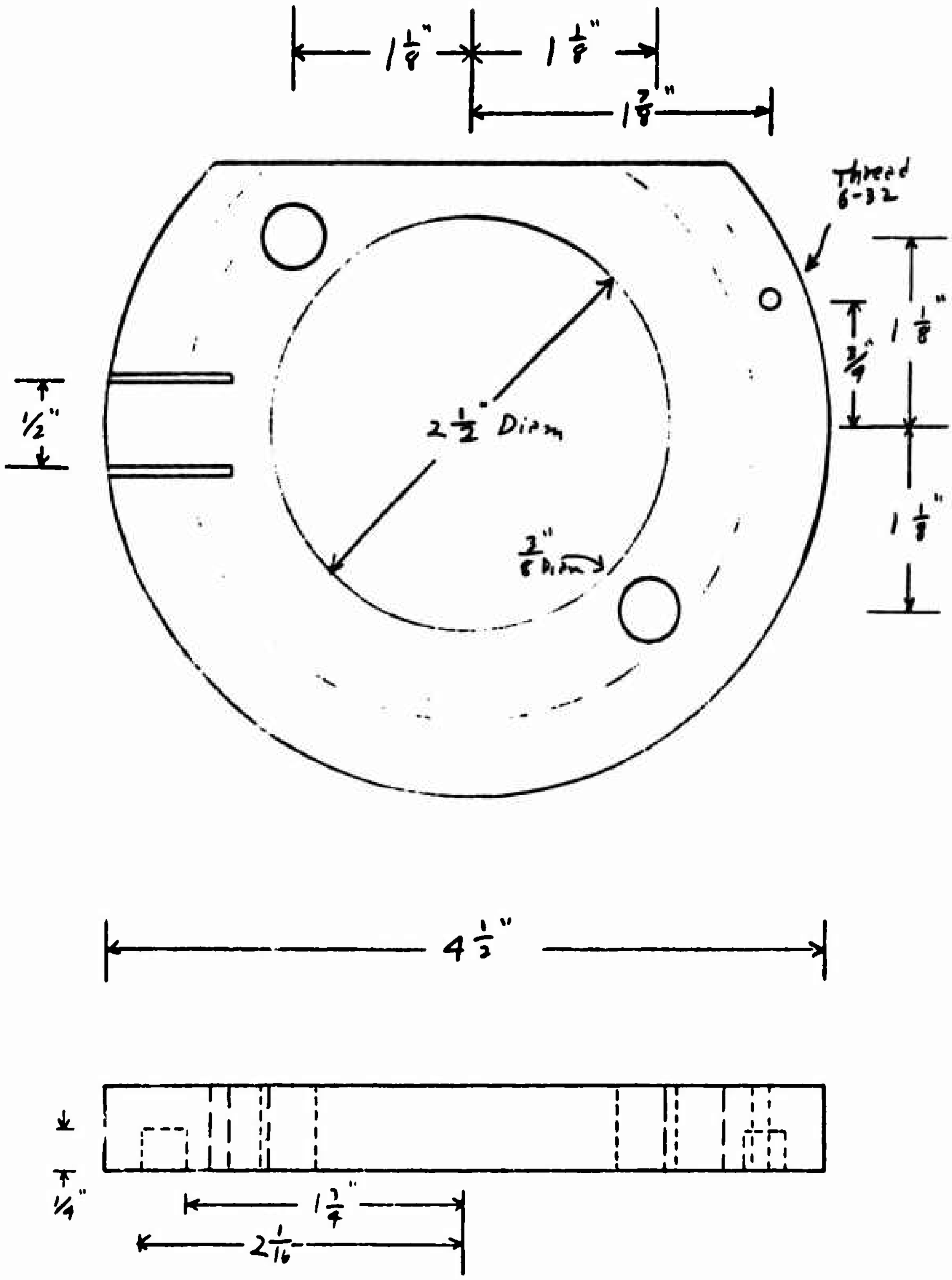
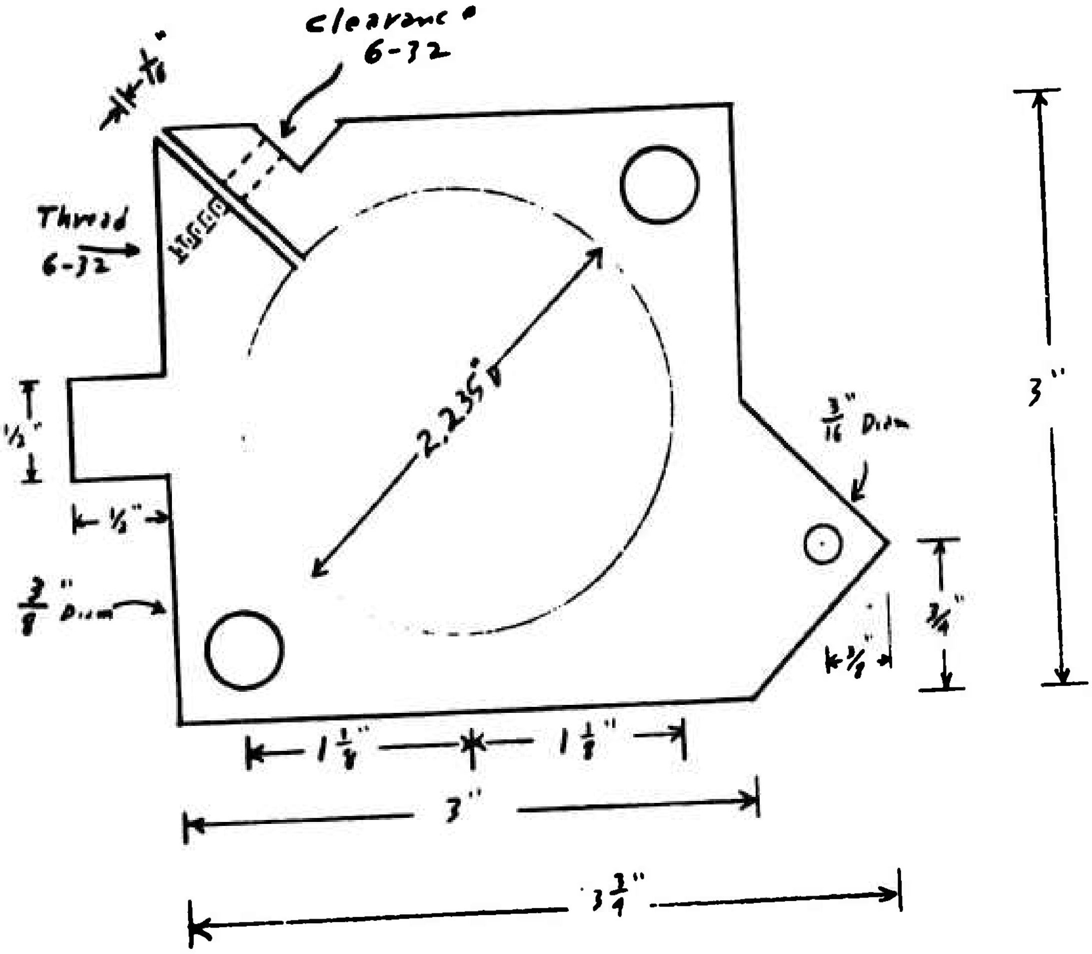
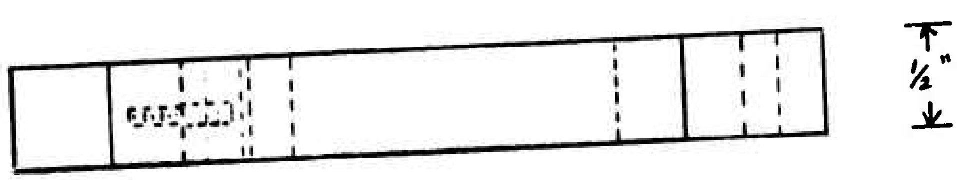


Figure 45 Calibration Fixture - Platform Drawing





Material 1/2" Phenolic

Figure 46 Calibration Fixture - Support Drawing

APPENDIX IV

ULTRASONIC RECORDINGS AND TEST DATA SUMMARY FOR THE SECOND ROTOR HUB

NOTE: This appendix includes representative ultrasonic test records, evaluation notes, and a test summary table for the second rotor hub. These data and analyses are intended to be illustrative of the magnitude of effort necessary to perform an ultrasonic inspection of a rotor hub and to evaluate the data. The 35 C-scan records were reduced from 1:1 scaled recordings of the second rotor hub to fit the report format which has resulted in an appreciable loss in clarity in some instances. However, sufficient detail is evident to permit discussions of the ultrasonic test results for each individual inspection condition.

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TEST RESULTS SUMMARY TABLE

HUB NO. 2

			Standards				Receiver						Transducer			Record
Area	Hub Position	Gate	1st Type	Std. Sig %	2nd Type	Std. Sig %	Rec. Level	Freq.	Sens	Atten.	P R F	Water Path	Diam.	Freq.	Ser.No	Hub 2
Arm Fing	Arm Up	1/4 to 1/2"	3 - 1/4	75%	3 - 3/8	90%	20%	2.25MH	1.45	odb	1250 Hz	3 in.	3/8	12 MH Flat	9541	1,2,3,4
Arm Wall	Arm Up	1/2 to 1 3/4	3 - 1/2	90	3-1 3/4	75	20	2.25	1.3	0	1250	3 in.	3/4	10	9D238	5,8,11, 16
Arm Wall	Arm up	1 3/4 to 4 1/4	3-1 3/4	75	5- 4 1/4	100	20	2.25	1.05	0	1250	3 in.	3/4"	10	9D238	6,9,12, 15
Arm Wall	Arm Up	4 1/4 to 6 3/4	5 - 4 1/4	100	5-5 3/4	75	20	2.25	1.0	0	1250	3 in.	3/4"	10	9D238	7,10,13, 14
Hub Cntr	Arms up	1/2 to 6 1/2	5 - 1/2	100	5-5 3/4	75	20	2.25	0.85	0	1250	3 in.	3/4"	10	9D238	19,20
Lug	Arms up	1/2 to 2 3/4	5 - 1/2	80	5-2 3/4	100	20	2.25	0.7	0	1250	3 in.	3/4"	10	9D238	22,23, 24
Hub Cntr	Arms down	1/2 to 6 1/2	5 -1/2	100	5-5 3/4	70	20	2.25	0.75	0	1250	3 in.	3/4	10	9D238	26
Center Flange	Arms down	1/2 to 1 1/8	5 -1/2	75	5 - 1	75	20	2.25	0.75	0	500	3 in.	3/4"	10	9D238	27
Ramp	Arms down	Variable	5 -1/2	65	5 - 1	80	20	2.25	2.1	0	500	Variable	3/4"	15	2653	28,29,30, 31
Lug	Arms down	1/2 to 2 3/4	5- 1/2	75	5-2 3/4	100	20	2.25	0.75	0	500	3 in.	3/4"	10	9D238	32,33,34

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TEST RECORD REMARKS

HUB No. 2

Record #1 Arm Flange Arm A

No flaw equal to 3/64 at 3/8"
Gate 1/4 to 1/2, Level 20%. 3 3/8 90%.

Record #2 Arm Flange Arm B

No flaw equal to 3/64 at 3/8"
Some ridges and Die marks.

Record #3 Arm Flange Arm C

No flaw equal to 3/64 at 3/8"
Some patches give up to 27% signal 2/64.

Record #4 Arm Flange Arm D

No flaw equal to 3/64 at 3/8"
One patch 20% Signal 1.4/64.

Record #5 Arm Wall D 1/2 to 1 3/4"

No flaws shown.

Record #6 Arm Wall D 1 3/4" to 4 1/4"

Nothing comparable to 5/64 @ 4 1/4

Record #7 Arm Wall D 4 1/4" to 6 3/4"

Shows strong signals due to protruding or indented laminations, ranging from 1 1/2 to 3" down from front surface. Main roughness is projection at 1 1/2" and laminations at 2 - 2 1/2". Metal travel would not fall in gate set at 4 1/4 to 6 3/4". Water path to the 1 1/2 inch projection would fall at 6" metal travel, well inside the gate.

Record #8 Arm Wall C 1/2 to 1 3/4"

No flaws shown except a rough edge on outer surface where the wall meets the flange. There is an uneven surface in this area.

Record #9 Arm Wall C 1 3/4 to 4 1/4"

No flaws shown.

Record #10 Arm Wall C 4 1/4 to 6 3/4"

Shows many echos from protruding and recessed laminations.
Shows several echos from within the wall.

25% @ 5 1/2"	3/64 flat bottom
27% @ 5 3/8"	3/64
30% @ 4 1/2"	2/64
35% @ 4 1/2"	2/64

Record #11 Arm Wall B 1/2 to 1 3/4"

Shows several small patches that might indicate small flaws.

29% @ 1 3/4"	2/64 flat bottom
50% @ 1 1/3"	2/64

TEST RECORD REMARKS (CONTINUED)

Record #12 Arm Wall B 1/2 to 1 3/4"

Shows no flaws other than the rough walls. There are numerous depressions and projections on walls under flange at locations noted on record.

Record #13 Arm Wall B 4 1/4 to 5 3/4"

See comments for record #7. Several echos that may be flaws in metal.

50% @ 5 3/8 4/64 flat bottom

Long white patches fall about centered on the true edge of the well or pocket.

Record #14 Arm Wall A 4 1/4 to 6 3/4"

See comments on Record #7

Large signals from rough sides. No indication of flaws in the metal.

Record #15 Arm Wall A 1 3/4to 4 1/4"

The point marked 38% @ 2" deep is exactly at the location of a deep step. Metal path = 2.0".

2.0" Deep Sharp Depression.

Record #16 Arm Wall A 1/2 to 1 3/4"

No indication of flaws in metal. Has bumps and rough surface on filet where flange joins wall which may cause the signals noted.

Largest signal 40% @ 1" 2/64 flat bottom.

Record #17 Hub Center - Arms up Gated Back Echo

This record seems in conclusive. #18 gives a better pattern.

Record #18 Hub Center - Arms Up Gated Back Echo

Collumnated to 1/4" Diameter

Pattern does not really fit the part. Ring on face is 10 3/4" Dia.
Record of ring is 9 3/8 Dia.

Record # 19 Hub Center - Arms Up 1/2 to 6 1/2"

Many signals but nearly all are quite small.
Largest is 32% @ 5 1/2" 3/64" flat bottom hole
The shoulder at 6 1/4" obscures some of the signals shown in #20.

Record #20 Hub Center - Arms Up 2 3/4 to 3 3/4"

Narrowed gate from #19 does not show some of the signals from #19.
Does show some spots at 3 3/4 that were obscured by the shoulder at 6 1/4".
Largest signal 30% @ 3 3/4 3/64.

TEST RECORD REMARKS ((CONTINUED)

Record #21 Lug A - Arms Up 1/2 to 2 3/4"

Sensitivity is so high we do not get a good record. Stds 3/64

Record #22 Lug A - Arms Up 1/2 to 2 3/4"

Stds changed to 5 - 1/2 and 5 - 2 3/4.
Shows no flaws. Using Video Sync to get edge marker we have problem with lip or flashing acts as ist surface to trigger gate and top of part then falls in gate.

Record #23 Lug C - Arms Up 1/2 to 2 3/4"

Shows on small flaw. Assuming that the 5 - 2 3/4 gives 100%.
Then 20% @ 2 1/2" 2/64 flat bottom hole.

Record #24 Lug D - Arms Up 1/2 to 2 3/4"

Shows no flaws.

Record #25 Hub Center - Arms Down Back Surface

Shows no flaw.

Record #26 Hub Center - Arms Down 1/2 to 6 1/2"

Numerous rather small signals and several fairly large ones.

30% @ 5" 3/64 flat bottom hole
46% @ 4" 4/64
50% @ 4 3/4" 4/64
65% @ 4 5/8" 5/64

Record #27 Center Section Flange 1/2 - 1 1/8"

Some multiples from shoulder with reduced water path.

Numerous spots show small signal.
25% @ 1" 3/64 flat bottom hole.

Record #28 Arm B Ramp- Arms Down 1/2 to 1"

No flaws indicated.

Record #29 Arm A Ramp - Arms Down 1/2 to 1"

No flaws indicated.

Record #30 Arm C - Ramp - Arms Down 1/2 to 1"

No flaws indicated.

Record #31 Arm D - Ramp - Arms Down 1/2 to 1"

No flaws indicated.

TEST RECORD REMARKS (CONCLUDED)

Record #32	Lug D - Arms Down	1/2 to 2 3/4"

Shows one small spot
20% @ 2 1/2" 2/64

Record #33	Lug A - Arms Down	1/2 to 2 3/4"

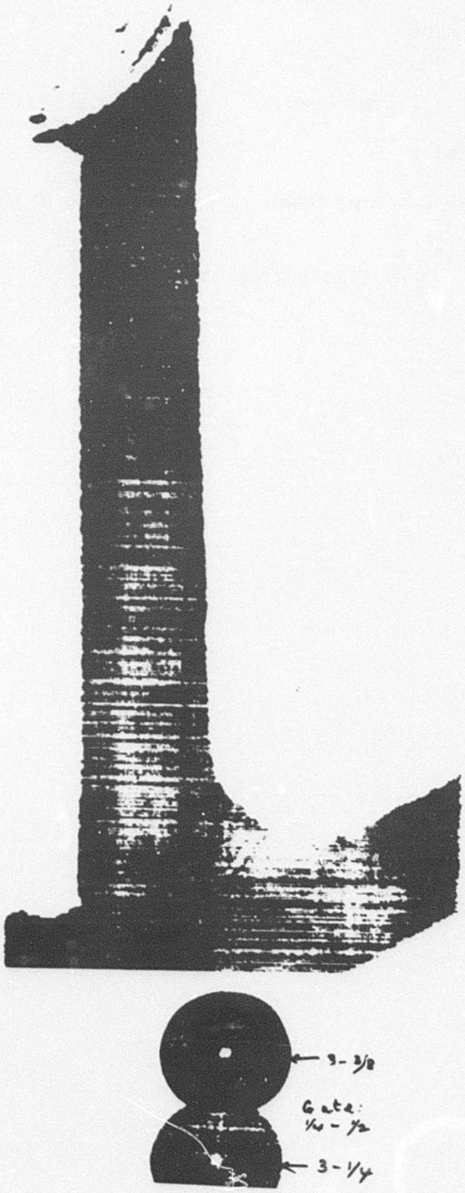
No flaws indicated

Record #34	Lug C - Arms Down	1/2 to 2 3/4"

Several small signals
30% @ 1 1/8" 3/64 flat bottom hole.

arm Flange
[illegible] up

Set 1
Hub 2

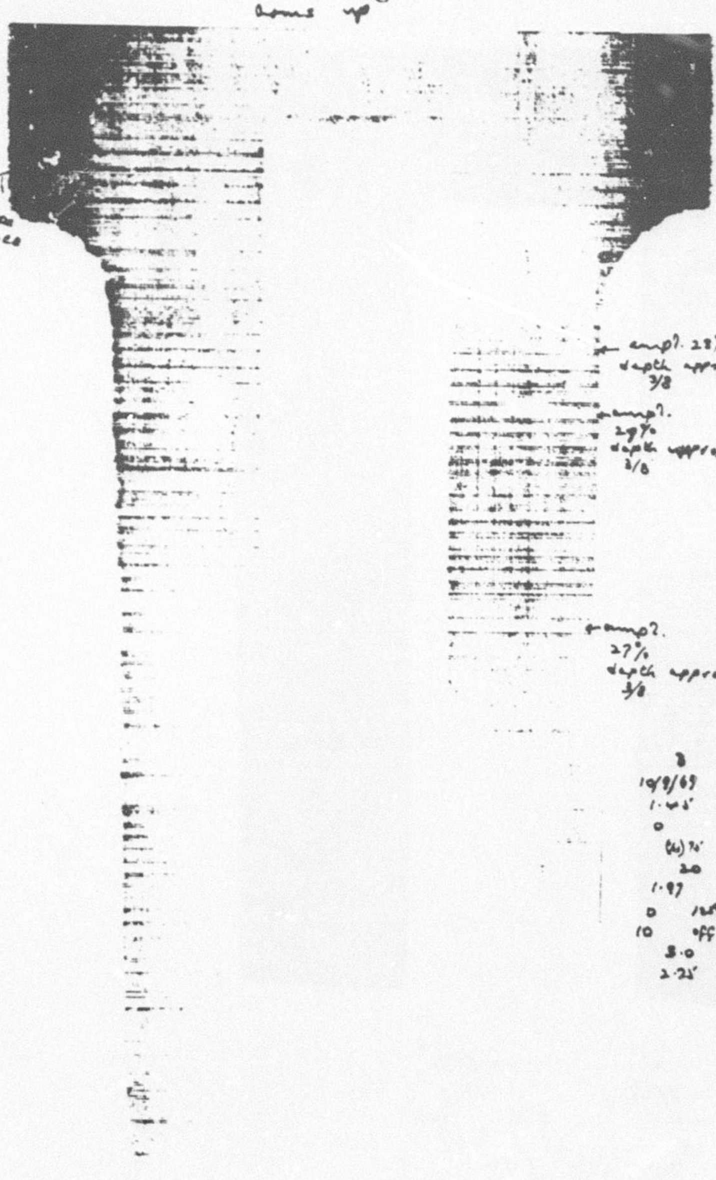


1 Hub #2
10/9/69 12 3/8
1.445 F905 95'4 3/16
0 3-1/4 3-3/8 6-4
(0.475) 72(90) 707
[illegible] 725 7051
1.97 [illegible] 1 8051
0 1250 V.S. Gate
10 off
3.0
2.25

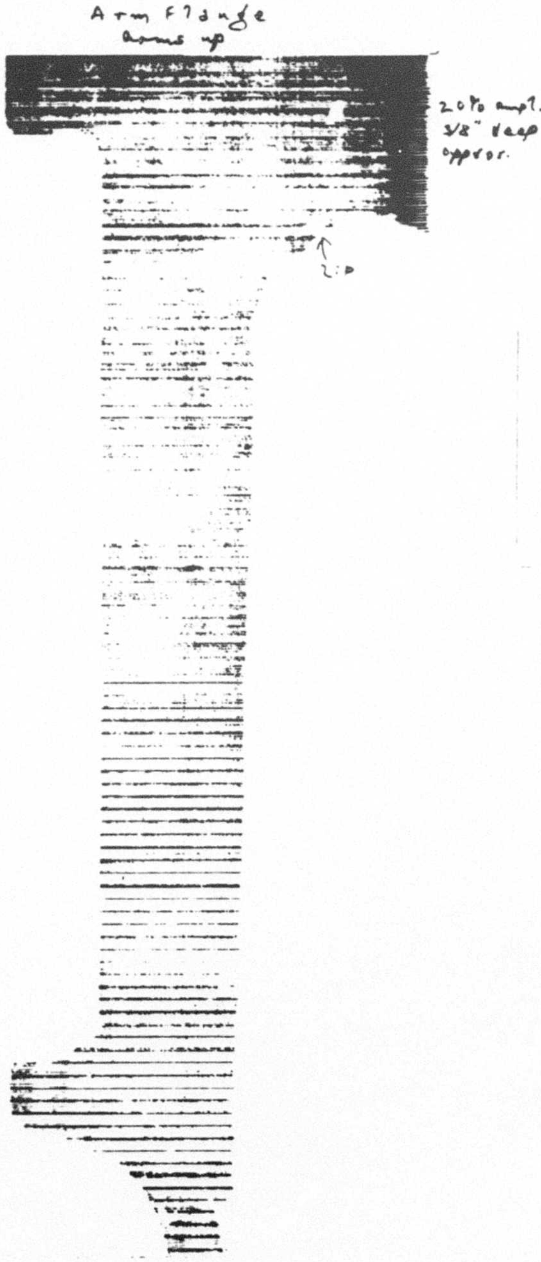
Attenuation Ratio:
Test std. Hub
120 90

arm Flanges

2	Hub #2	
10/9/69	12	3/8
1.45	Flat 9541	51L
0	3-1/4 3-3/8	6-4
(3/4)75	(3/8)90	707
30	72.5	7051
1.97	2 9052 1	8051
0 1250	V. S. [illegible]	
10 off		
3.0		
2.25		

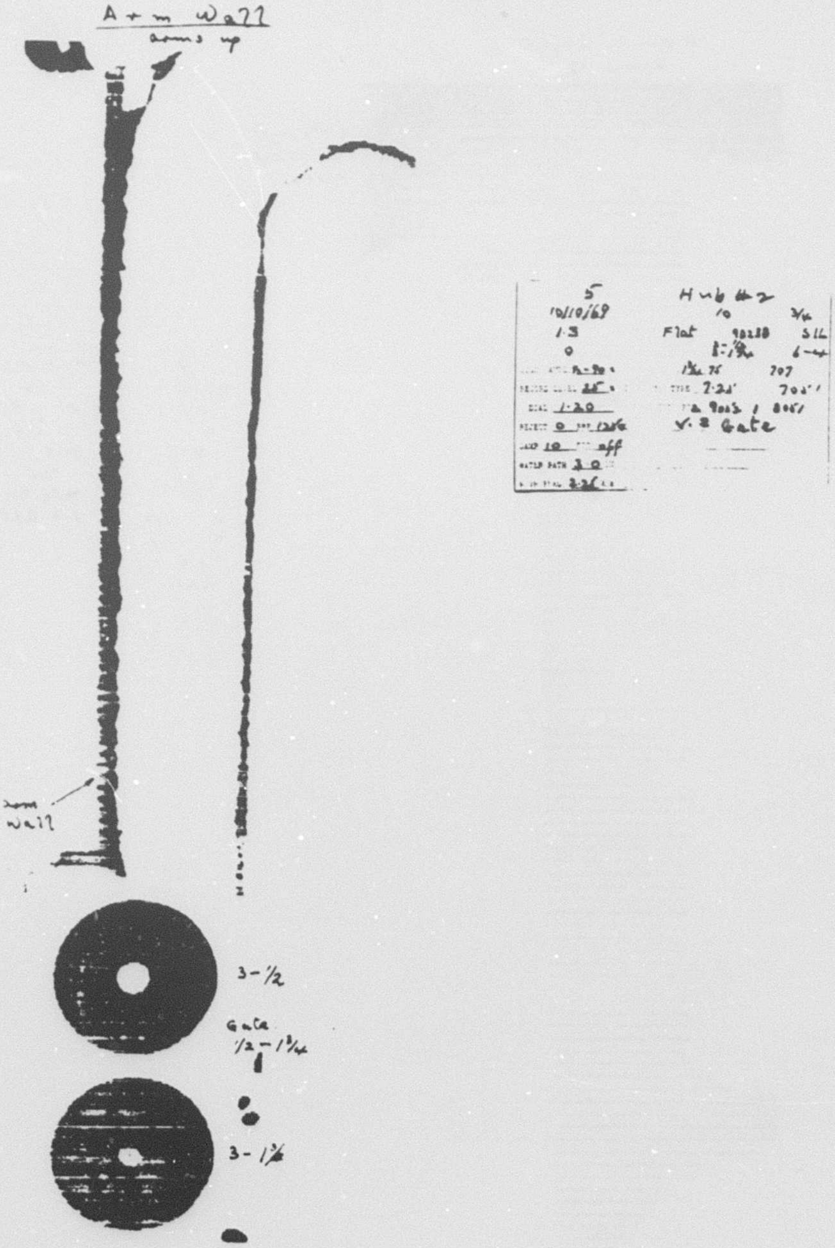


Arm Flanges
down up
Piece of
lead tape
on surface
ampl. 28%
depth approx
3/8
ampl.
29%
depth approx.
3/8
ampl.
27%
depth approx.
3/8
8
10/9/69
1.45
0
(4) 70
20
1.97
0 1250
10 off
3.0
2.25
Hub #2
12 3/8
Flat [illegible] 8K
3-4
3-3/8 6-4
(3/8) 90 707
72.5 [illegible]
2 [illegible] 1 [illegible]
V.S. Gate



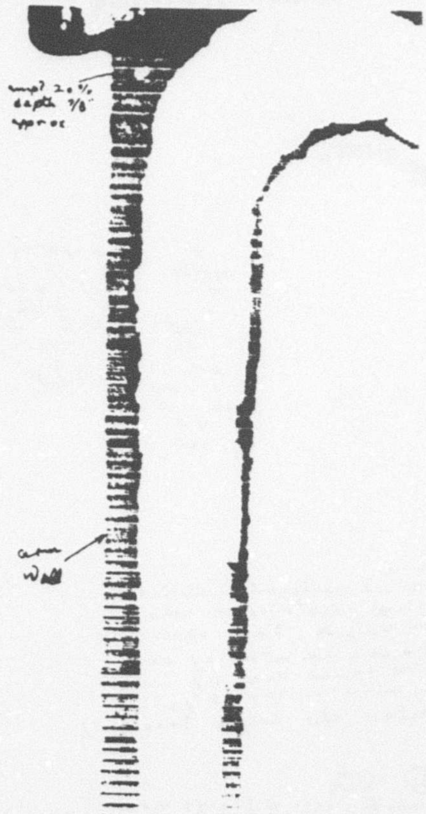
4
10/9/69
1.45
0
90(75)
30
1.97
0 1205
10 off
3.0
2.25

Hub # 2
12 .3/8
Flat. 95=1 SIL
3-3/8 6-4.
(3/8) 90 707
725 705-1
725 (1 Bolt) Fig. 905-2
V.S. Gate

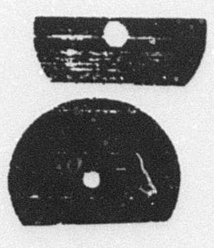


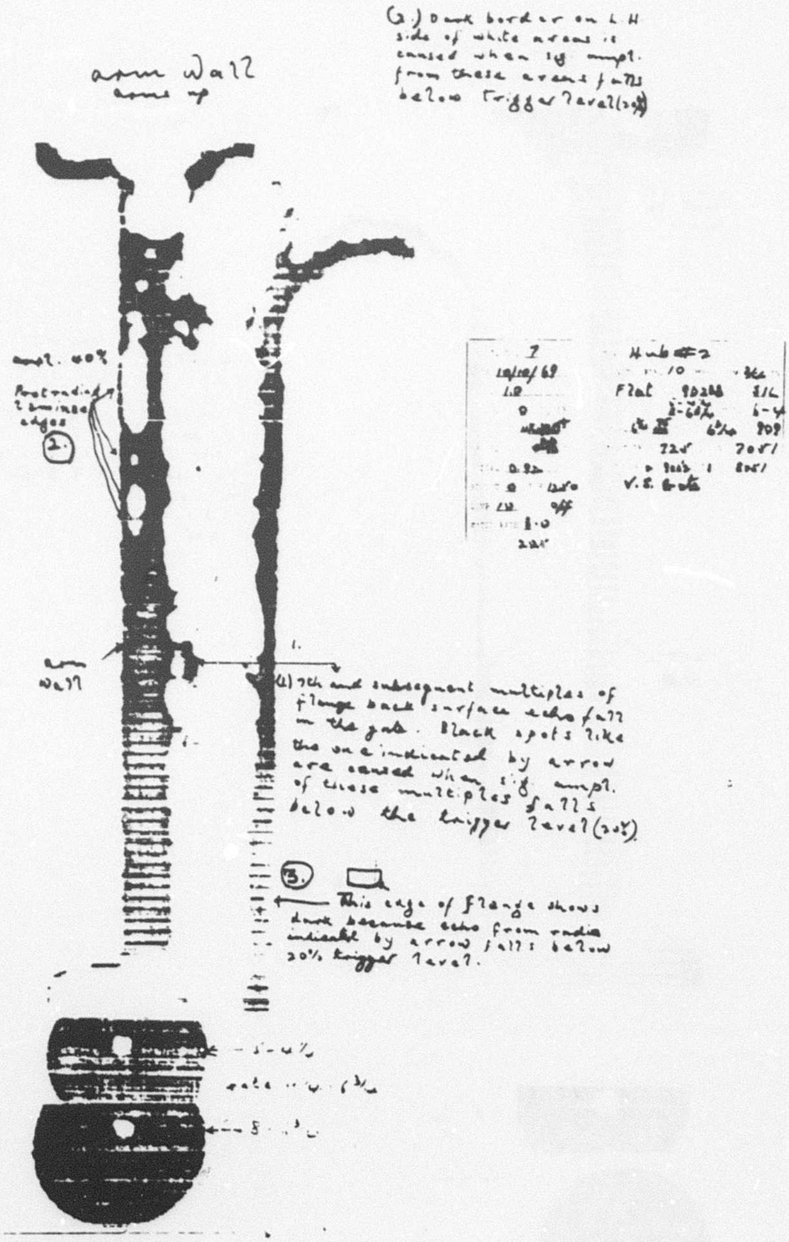
Arm Wall
arms up
arm wall
3-1/2
Gate
1/2-1 3/4
3-1 3/4
5
Hub #2
10/10/69
10
3/4
1.3
Flat
90238
SIL
0
6-4
707
1.20
0
off
10
3.0
7.25
V. 2 Gate

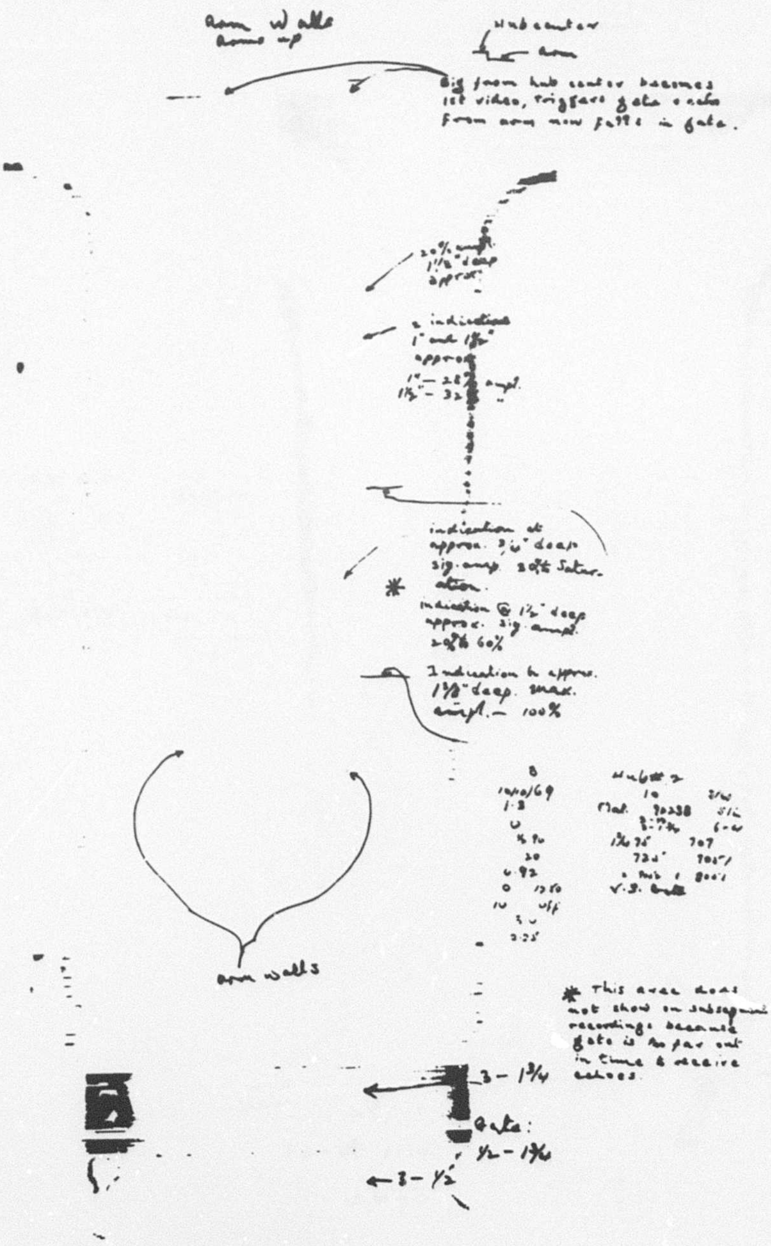
Arm Wall
arms up

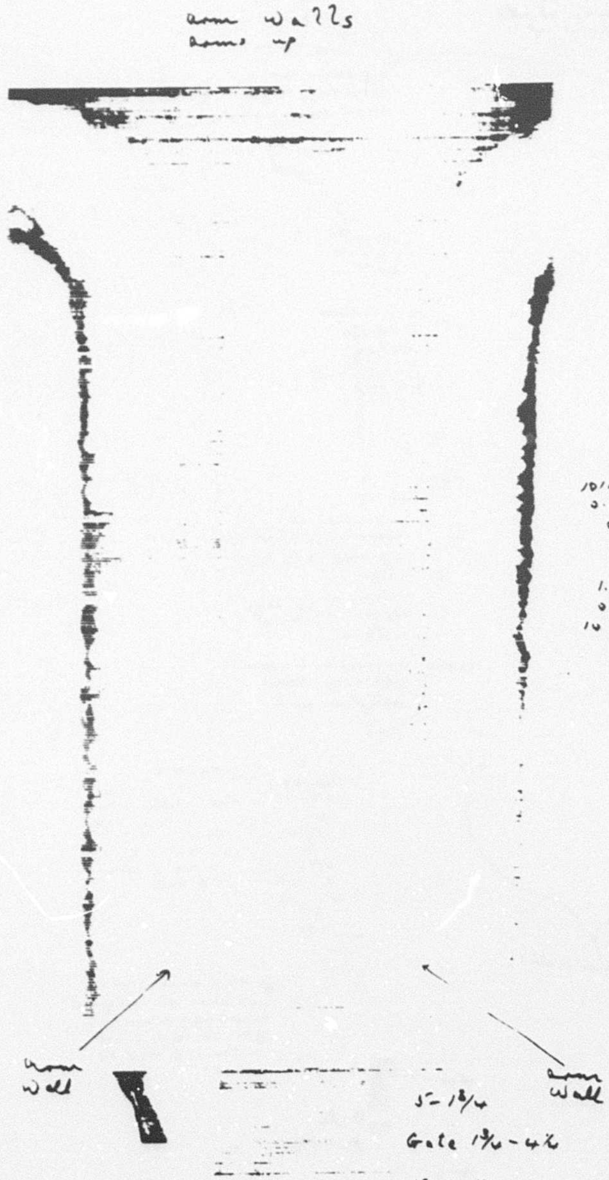


6	Hub #2		
10/10/68		10	3/4
0.7	Flat	90238	S/L
D		6-14/4 6-4/4	6-4
3/4 75'	Weld		None
20		72.5'	70+7
0.92		2 Posts	Post
0 126	Y.S. Gale		
10 off			
3.0			
2.25			



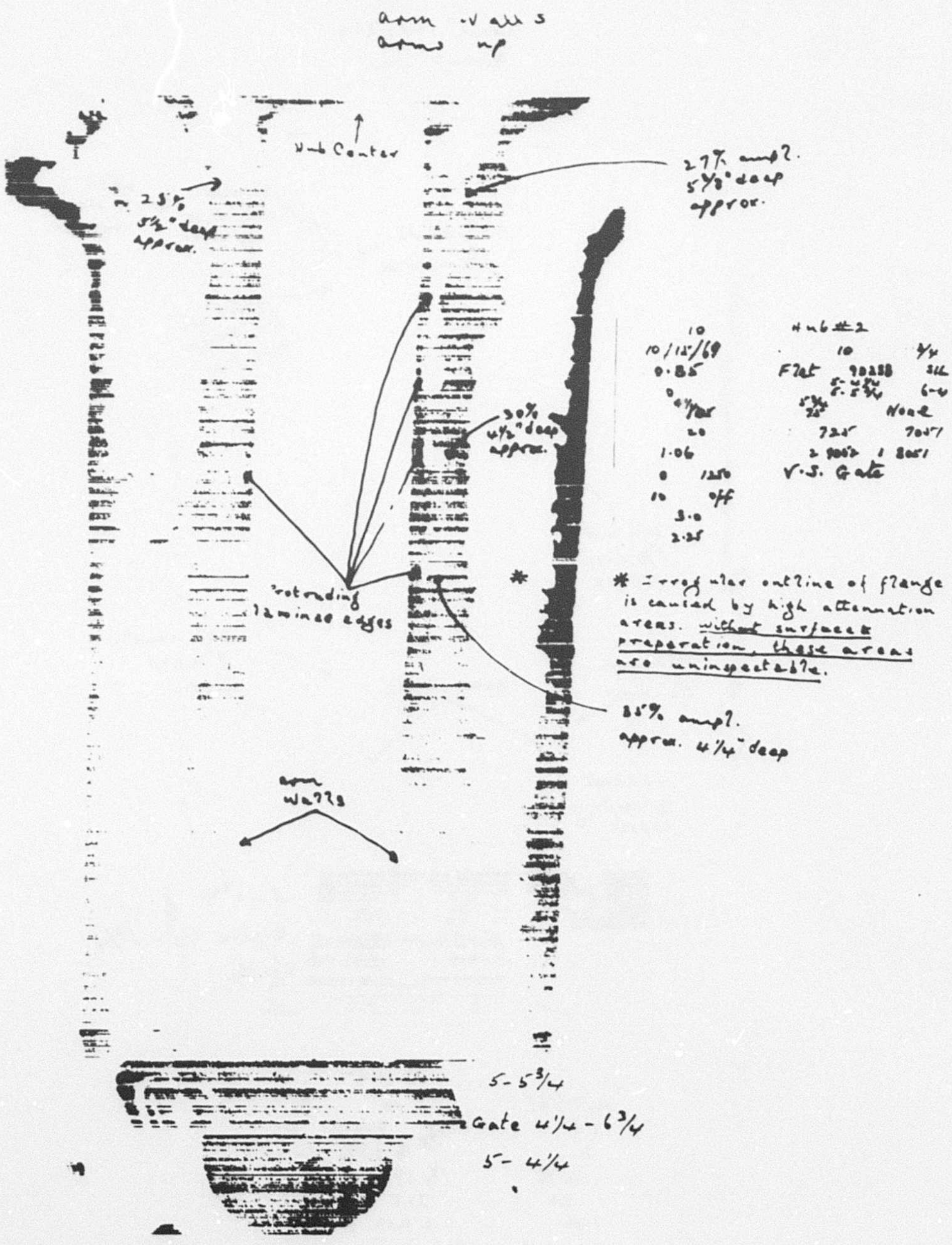

(2.) Dark border on L.H side of white areas is caused when sig. ampl. from these areas falls below trigger level (20%)
arm wall
arm up
ampl. 40%
Poor radius & laminar edges
2.
Hub #2
Flat
V.S. Grote
1.
arm wall
(1) 7th and subsequent multiples of flange back surface echo fall in the gate. Black spots like the one indicated by arrow are caused when sig. ampl. of these multiples falls below the trigger level (20%)
3.
This edge of flange shows dark because echo from radius indicated by arrow falls below 20% trigger level.


Arm Walls
Arms up
Hub center
Arm
Sig from hub center becomes 1st video, triggers gate echo from arm now falls in gate.
20% ampl. 1½" deep approx.
2 indications 1" and 1½" approx.
1" – 28% ampl.
1½" – 32% "
indication at approx. 3/16" deep sig. amp. 30% Saturation.
*
indication @ 1½" deep approx. sig. ampl. 20% to 60%
Indication to approx. 1⅜" deep. max. ampl. – 100%
arm walls
* This area does not show on subsequent recordings because gate is too far out in time to receive echoes.
3 – 1¾
Gate:
½ – 1⅜
← 3 – ½



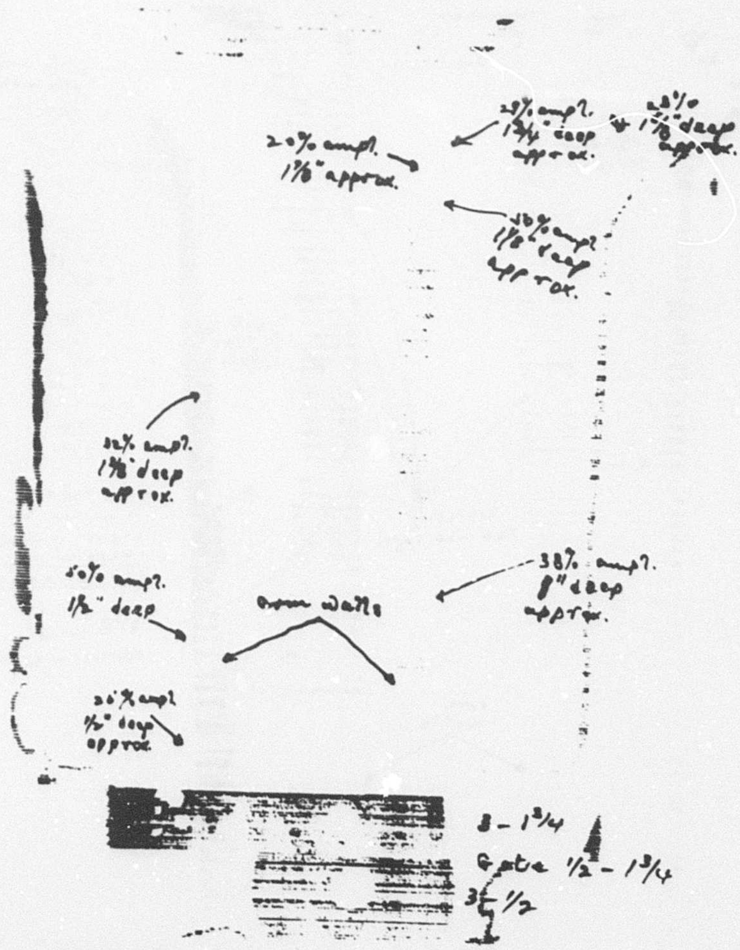
9
10/13/69
0.7
0
14.85'
30
1.01
0 12.50
14 off
3.0
3.25'

Hub #2
10 3/4
Frac 10218 5/L
5'-1 3/4
5'-4 3/4 6-4
46 81 None
72.5' 70.5'
2 90.5 1 300'
V.S. Gate



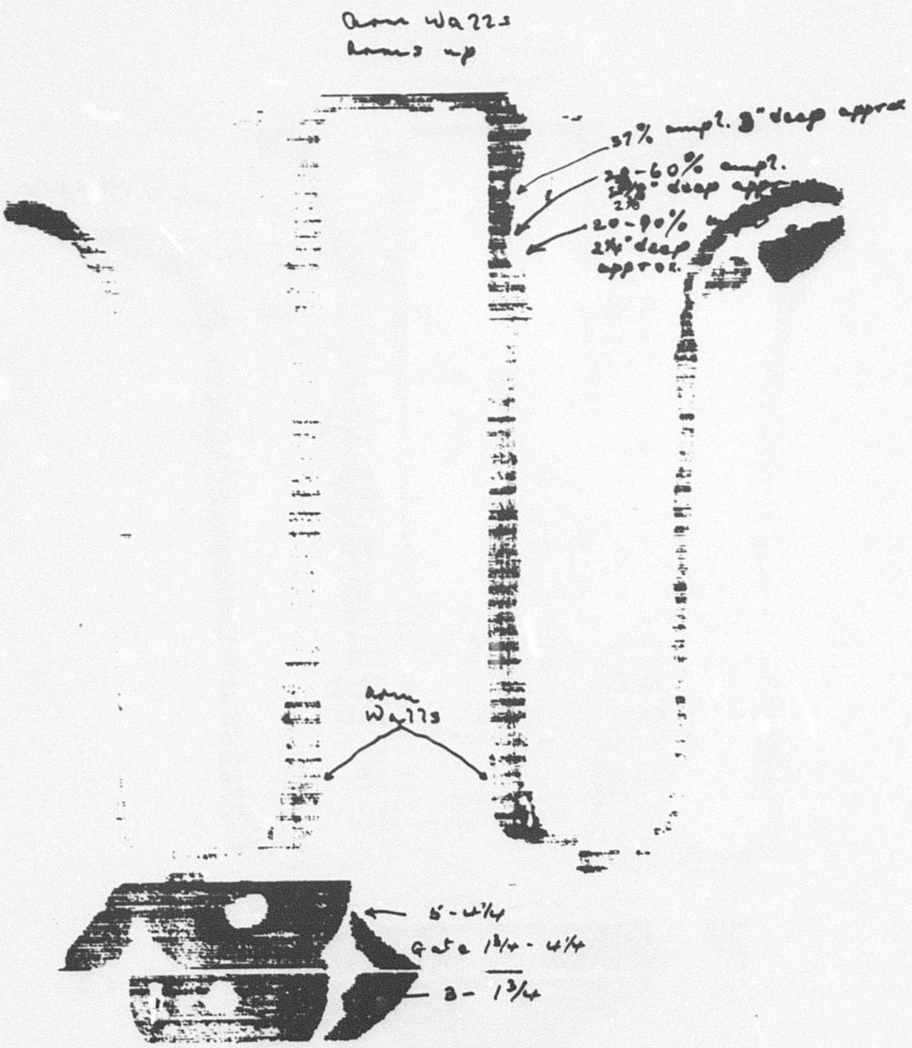
Hub Center
27% ampl.
5 3/8" deep
approx.
25%
5 1/2" deep
approx.
30%
4 1/2" deep
approx.
Protruding
laminae edges
10
10/15/69
0.85
20
1.06
0 1250
10 off
3.0
2.25
Hub #2
10 1/4
Flat 90238 SIL
6-4
None
725 7051
V.S. Gate
* Irregular outline of flange is caused by high attenuation areas. without surface preparation, these areas are uninspectable.
85% ampl.
approx. 4 1/4" deep
arm walls
5 - 5 3/4
Gate 4 1/4 - 6 3/4
5 - 4 1/4

arm Walls
arms up

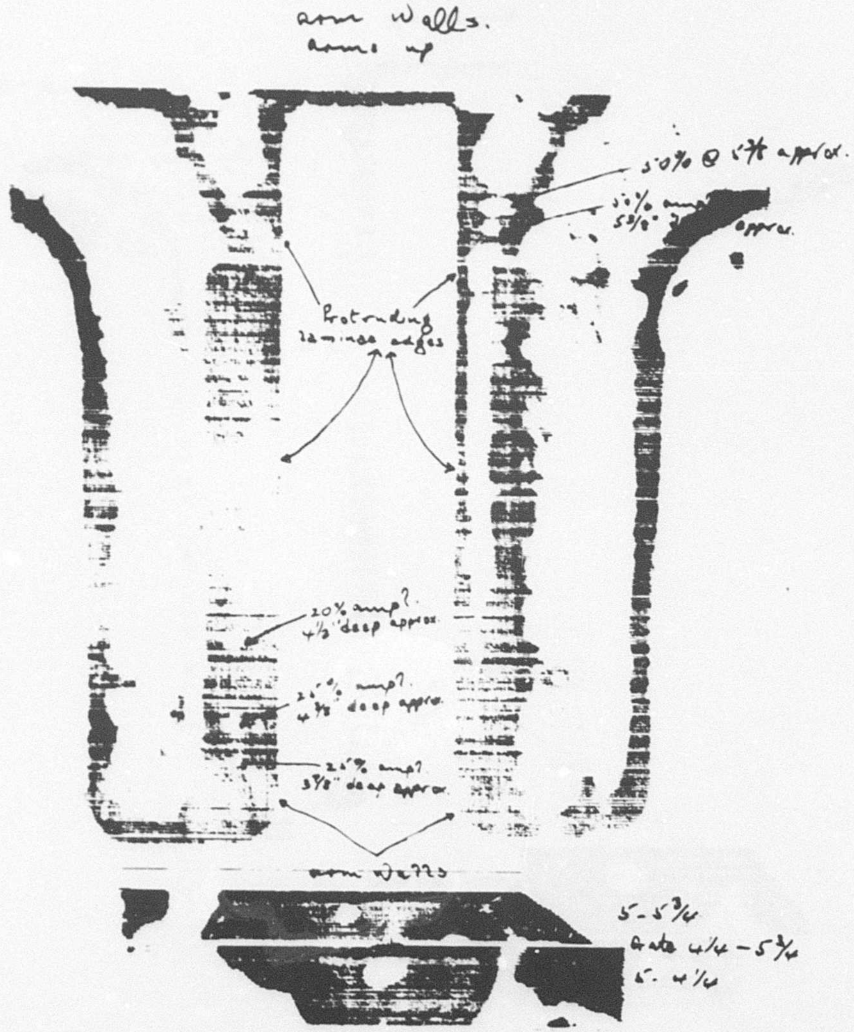


11
10/15/69
1.3
0
3/4 86
20
1.06
0 1206
10 off
8.0
2.25

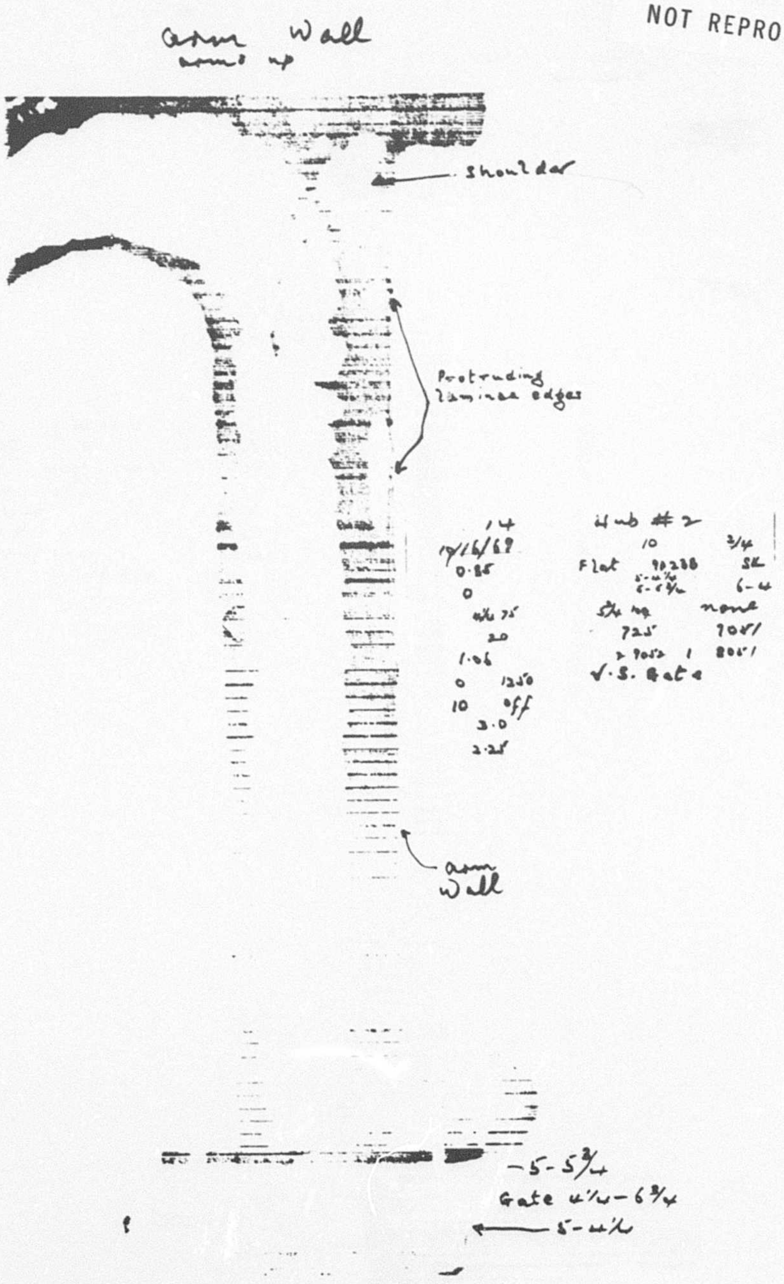
Hub # 2
10 3/4
Flat 92238 S/L
8-1/2; 8-1 3/4 6-4
1 3/4 79 807
725 9051
2 Pos 2 1 8051
V.2. Gate

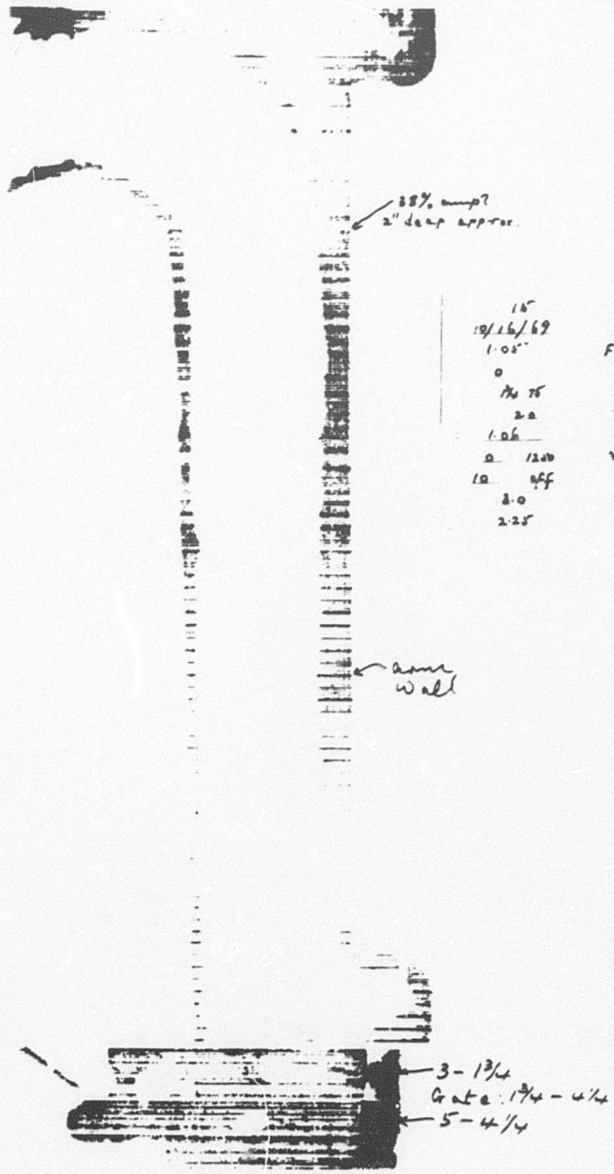


12 Hub #2
10/15/69 10 3/4
3.0 Flat 3.99 288 SIL
0 5 - 4 1/4 6-4
1 3/4/5 4 1/4 100+ 1 3/4 - 707
20 725 7057
1.06 2 9052 1 8051
0 1250 V.S. Gate
10 off
3.0
2.25



13	Hub #2	
10/15/69	10	3/4
1.25	Flat 90238	SIL
	5-4 1/4	
0	5-5 3/4	6-4
6 3/4 25	[illegible]	None
20	725	70%
1.05	2 90% 1	80%
0 12-30	V.S. Gate	
10 4F		
3.0		
225		

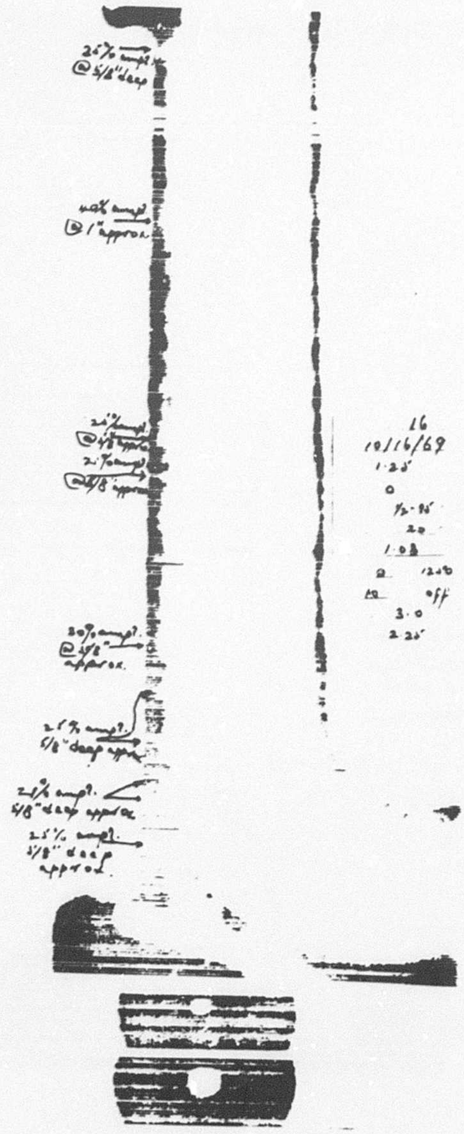

arm Wall
Shoulder
Protruding laminae edges
14
Hub #2
10
3/4
0.85
Flat
SK
0
6-4
none
20
725
1.06
0 1250
10 off
3.0
2.25
arm Wall
-5-5 3/4
Gate 4 1/4-6 3/4
5-4 1/4



15
10/16/69
1.05"
0
1/4 75
2.0
1.06
0 1200
10 off
3.0
2.25

H w S # 2
10 3/4
Flat 90208 S/L
3 - 1 3/4
5 - 4 1/4 6 - 4
4 1/4 100 none
725 7051
2 9052 1 8051
V. S. Gate

Arm Wall
arms up

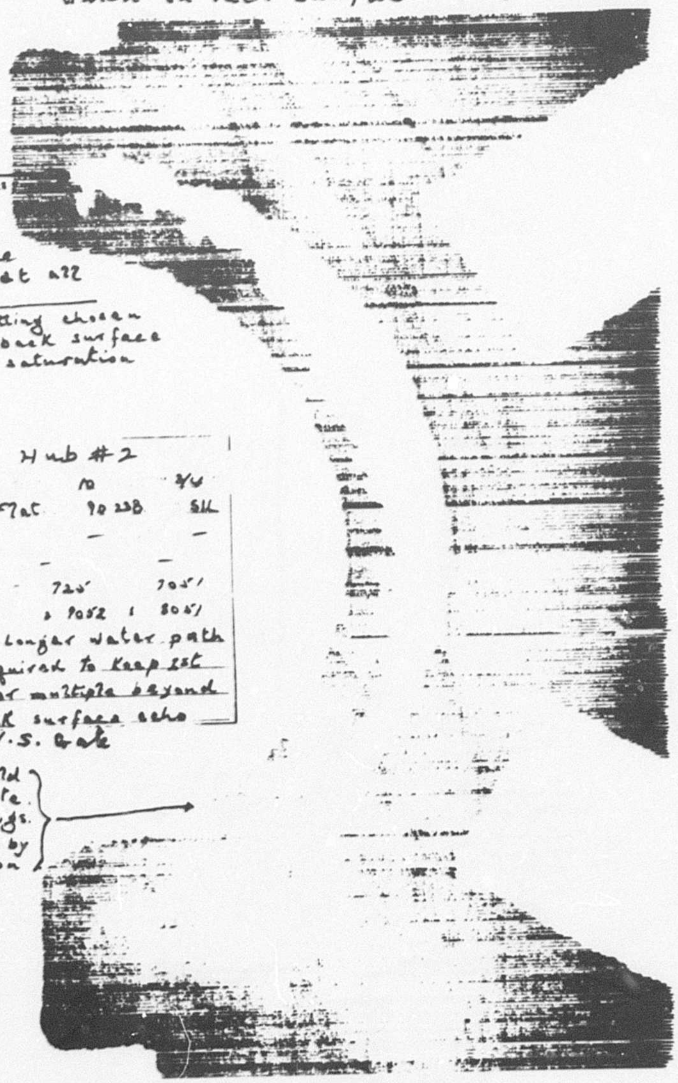


16
10/16/69
1.25
0
1/2 - 95
20
1.0B
2 1200
10 off
3.0
2.25

Hub # 2
10 3/4
Flat 90238 31L
3-1/2
3-1 3/4 6-4
1/4 75 707
720 705'
2 9002 1 805"
V.S. Gate

Hub Center
Arms up

Gated on back surface echo



White indicates that in this area a back surface echo in excess of 20% amplitude was received at all times.

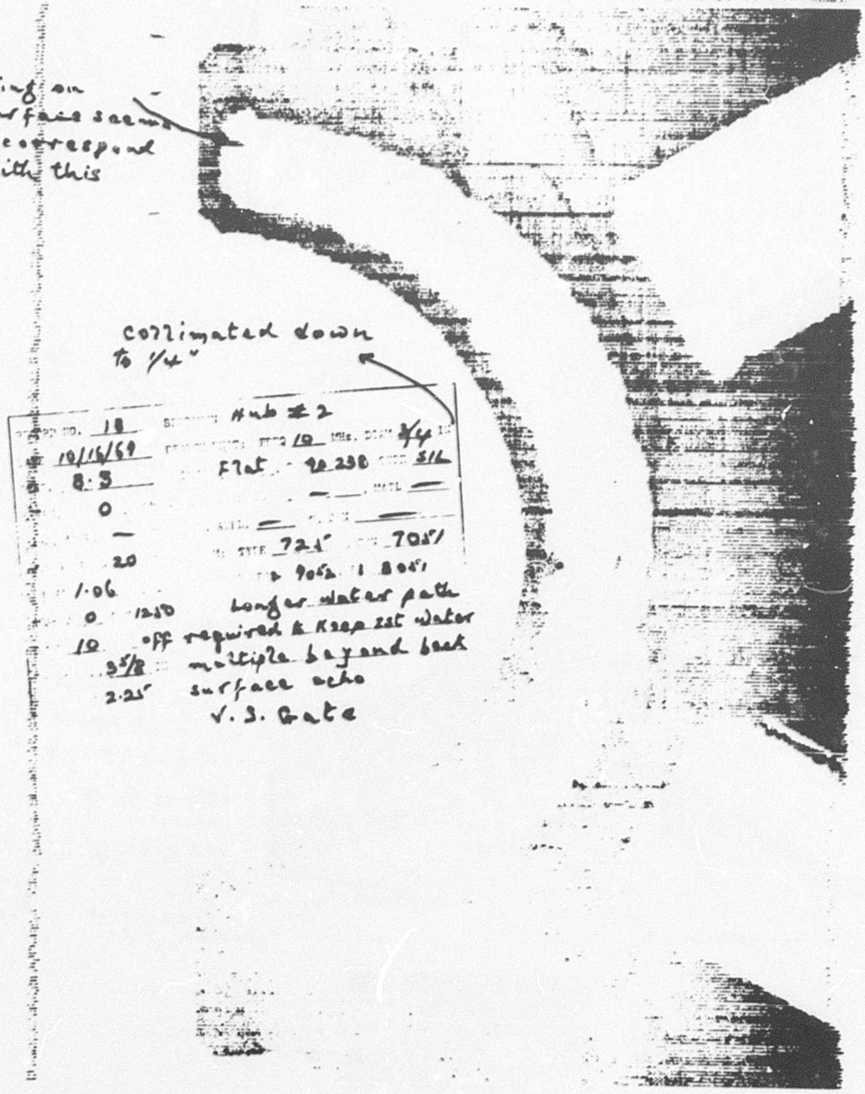
This gain setting chosen to keep max. back surface echo below saturation

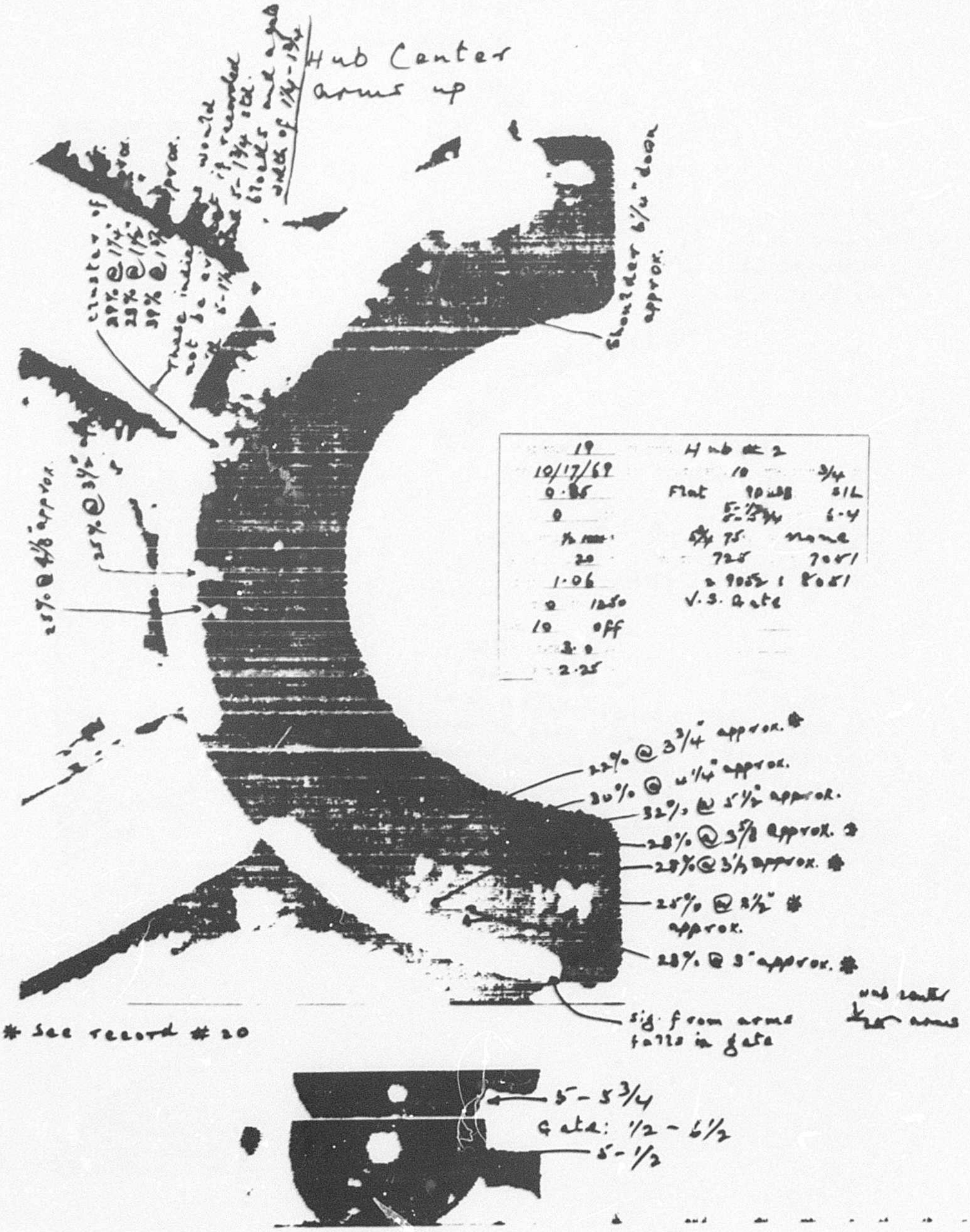
17 Hub #2
10/16/69 10 3/4
0.7 Flat 90 23B SIL
0 — —
— — —
20 725 7051
1 06 9052 1 8051
0 1230 Longer water path
10 (off) required to keep 1st
3 5/8 water multiple beyond
2.25 back surface echo
V.S. Gate

This area should normally be white. Low amplitude sigs. probably caused by surface condition

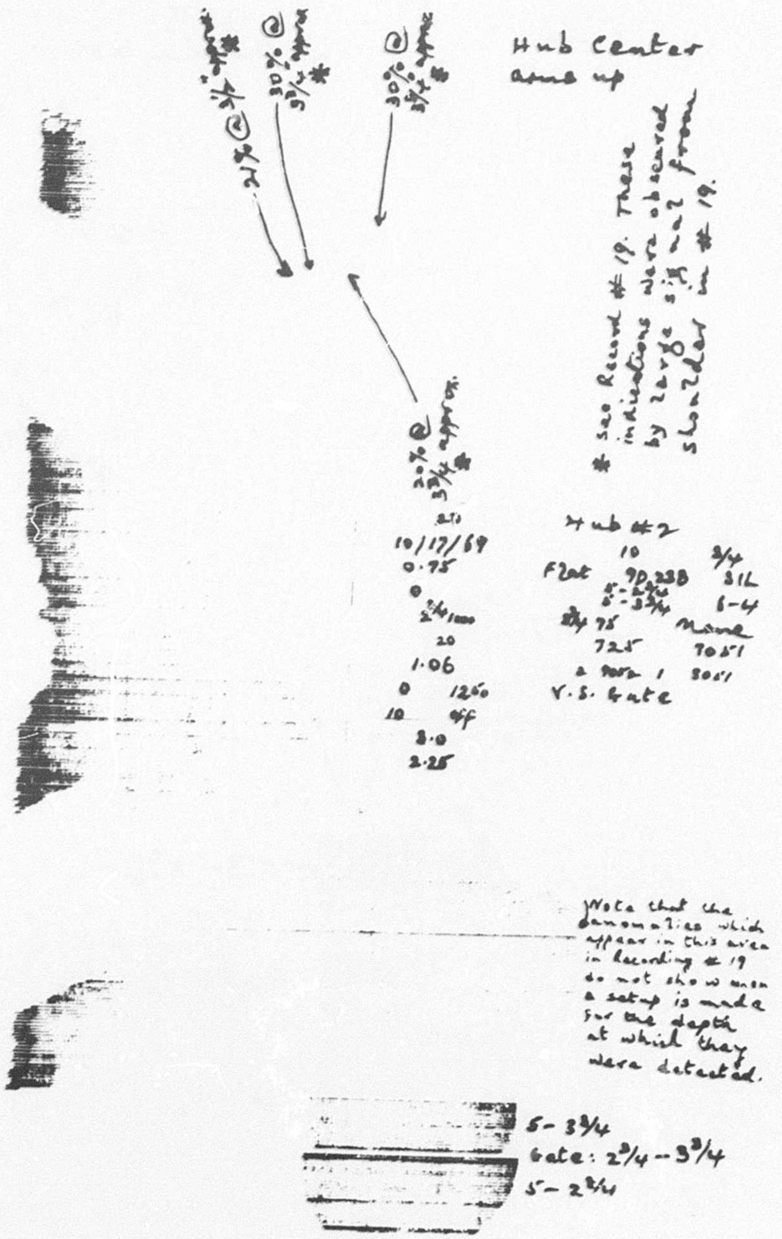
Hub Center
Arms up

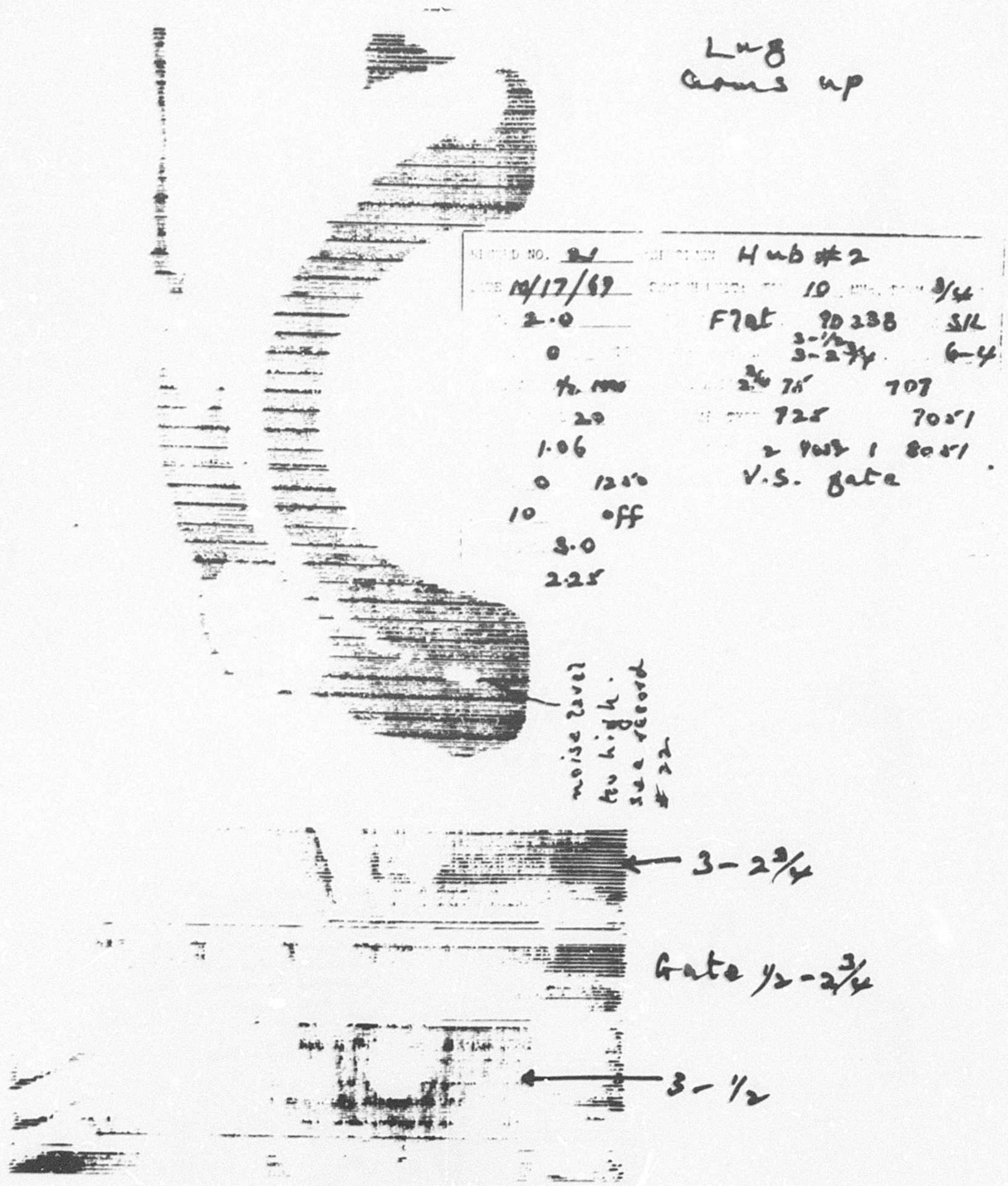
Gated on back surface echo





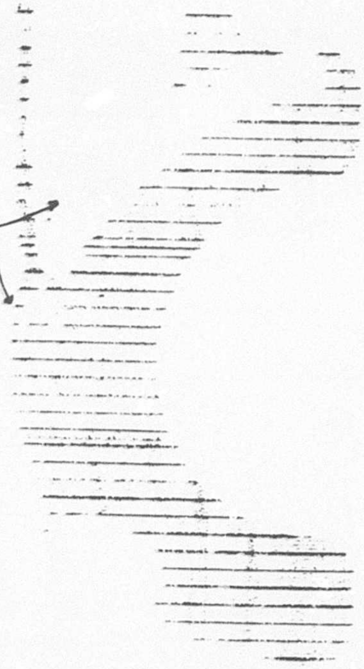
Hub Center
arms up
Shoulder 6¼" down approx.
19
Hub at 2
10/17/69
10
3/4
Flat
90 dB
SIL
0
6-4
75
none
20
725
1.06
V.S. Gate
10
off
2.25
22% @ 3¾" approx. *
30% @ 4¼" approx.
32% @ 5½" approx.
28% @ 3⅝ approx. *
28% @ 3½ approx. *
25% @ 2½" * approx.
28% @ 3" approx. *
25% @ 4⅞" approx.
25% @ 3½"
Sig. from arms falls in gate
* See record # 20
5 - 5¾
Gate: ½ - 6½
5 - ½


Hub Center
arms up
* see Record # 19. These
indications were observed
by large
shoulder in # 19.
10/17/69
0.75
1.06
1250
3.0
2.25
Hub #2
Flat
None
V.S. Gate
Note that the anomalies which appear in this area in Recording # 19 do not show when a setup is made for the depth at which they were detected.
5- 3¾
Gate: 2¾ - 3¾

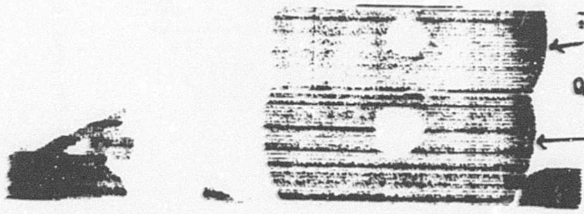


NOT REPRODUCIBLE

Sig. from lip becomes 1st video, causing sig. from surface of lug to fall in gate



Lug
Arms up

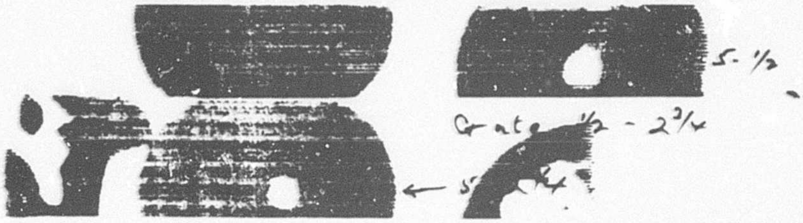


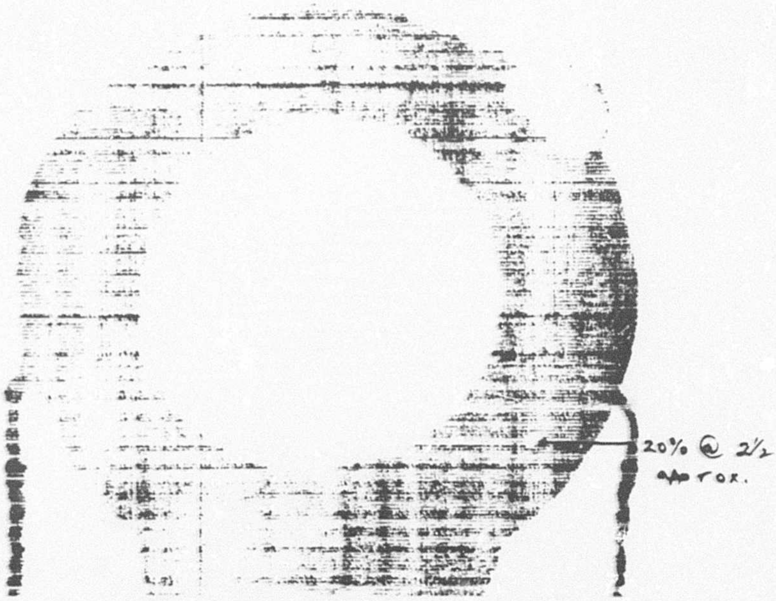
5-2 3/4
Gate 1/2 - 2 3/4
5-1/2

27
10/20/68
0.7
0
1/2 . 60
20
1.06
0 1250
10 off
3.0
2.25

Hub #2
10 3/4
Flat 9D238 S/L
5-1/2
5-2 3/4 6-4
3/4 1004 None
725 7051
2 9052 1 8051
V.S. Gate

NOT REPRODUCIBLE

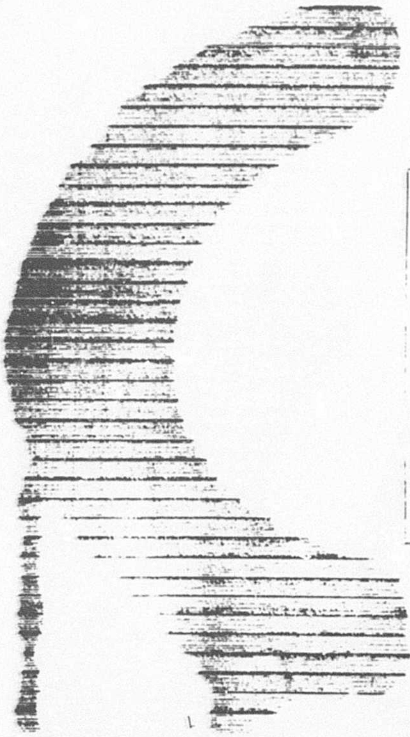




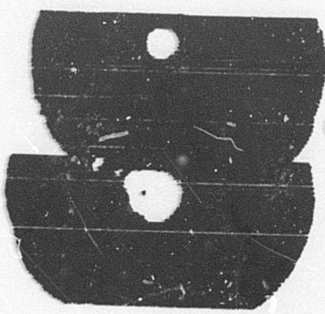
23	Hub # 2		
10/20/69		10	3/4
0.7	Flat	90238	S/L
0		5-1/2 5-2 3/4	6-4
1/2 60	3/4 100		none
20		725	705
1.06	2	9053 1	805
0 1250	Y.S. Gate		
10 off			
3.0			
2.25			

NOT REPRODUCIBLE

Lug
arms up



24		Hub #2	
10/20/69		10	3/4
0.7	Flat	90238	SIL
0		5-1/2 5-2 3/4	6-4
1/2 60		2 3/4 1000	none
20		725	7051
1.06		2 9052	1 8051
0 1250		r. s. Gate	
10 off			
3.0			
2.25			



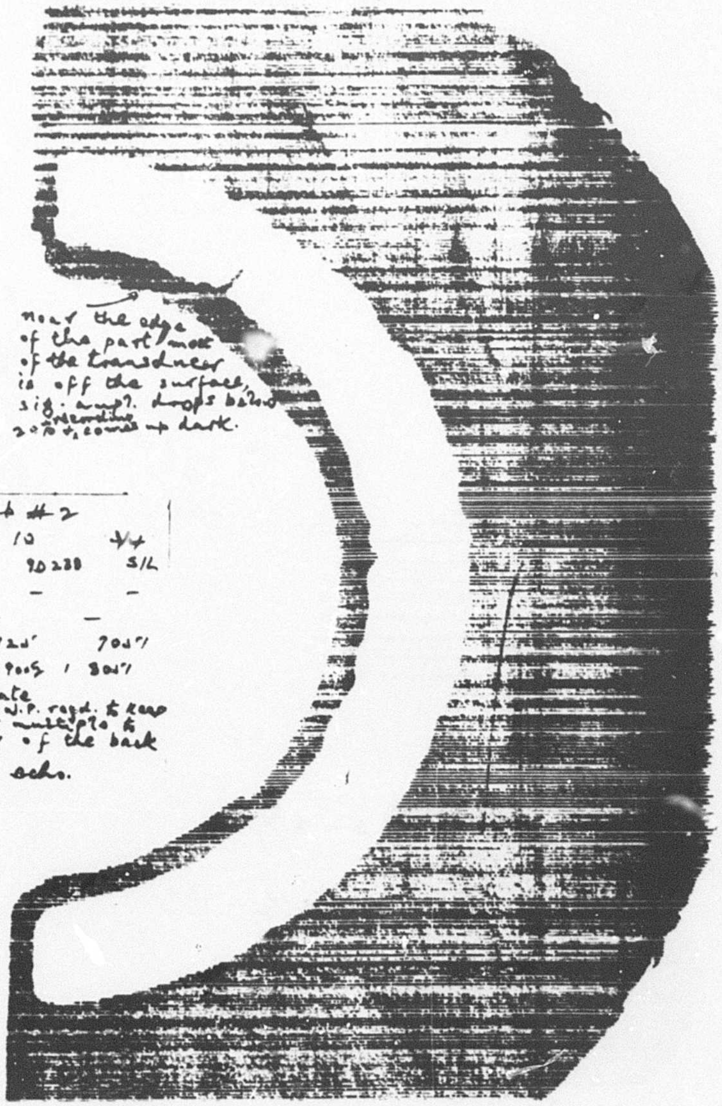
5-2 3/4

Gate 1/2-2 3/4

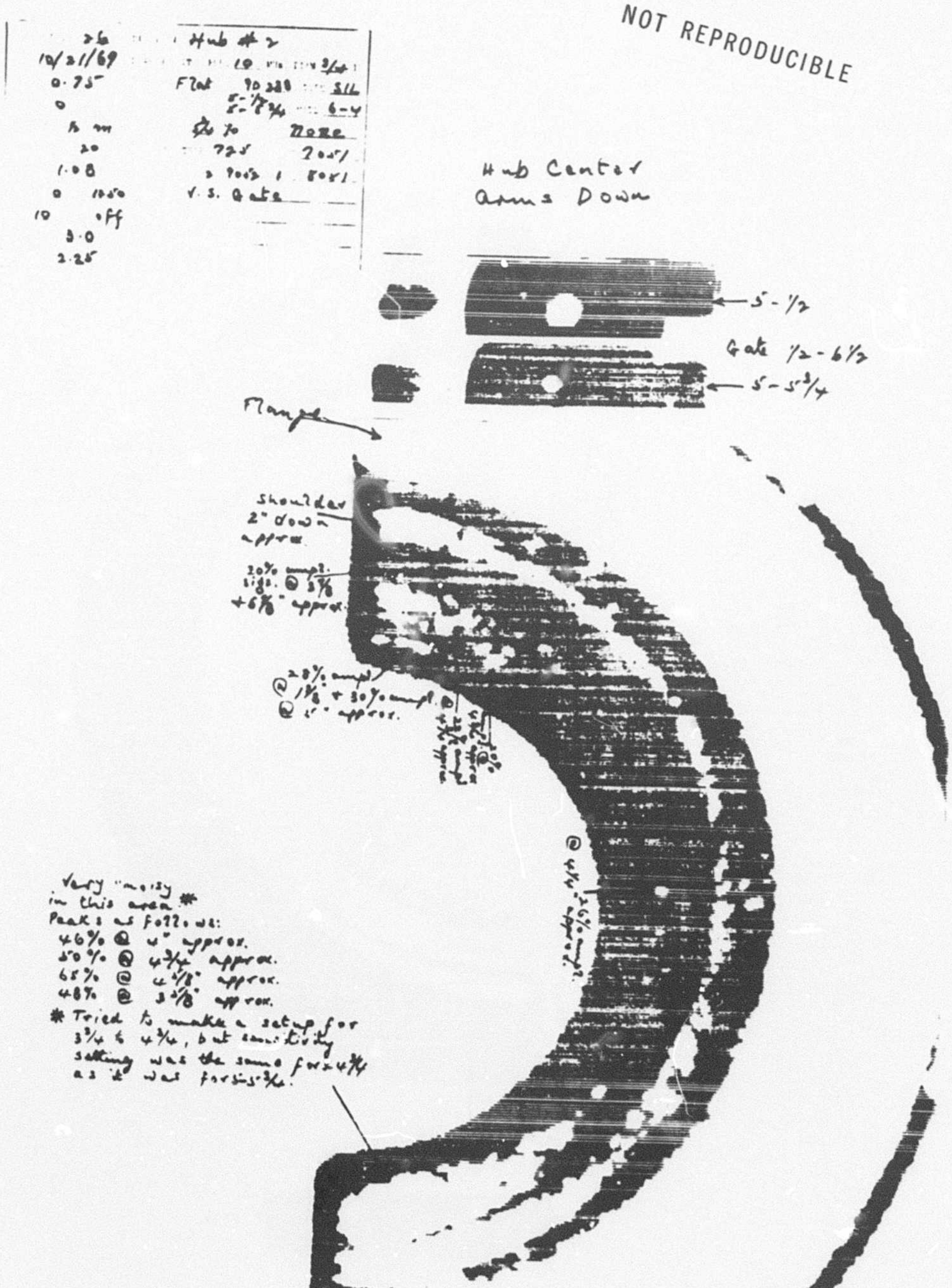
5-1/2

Hub Center
Arms Down

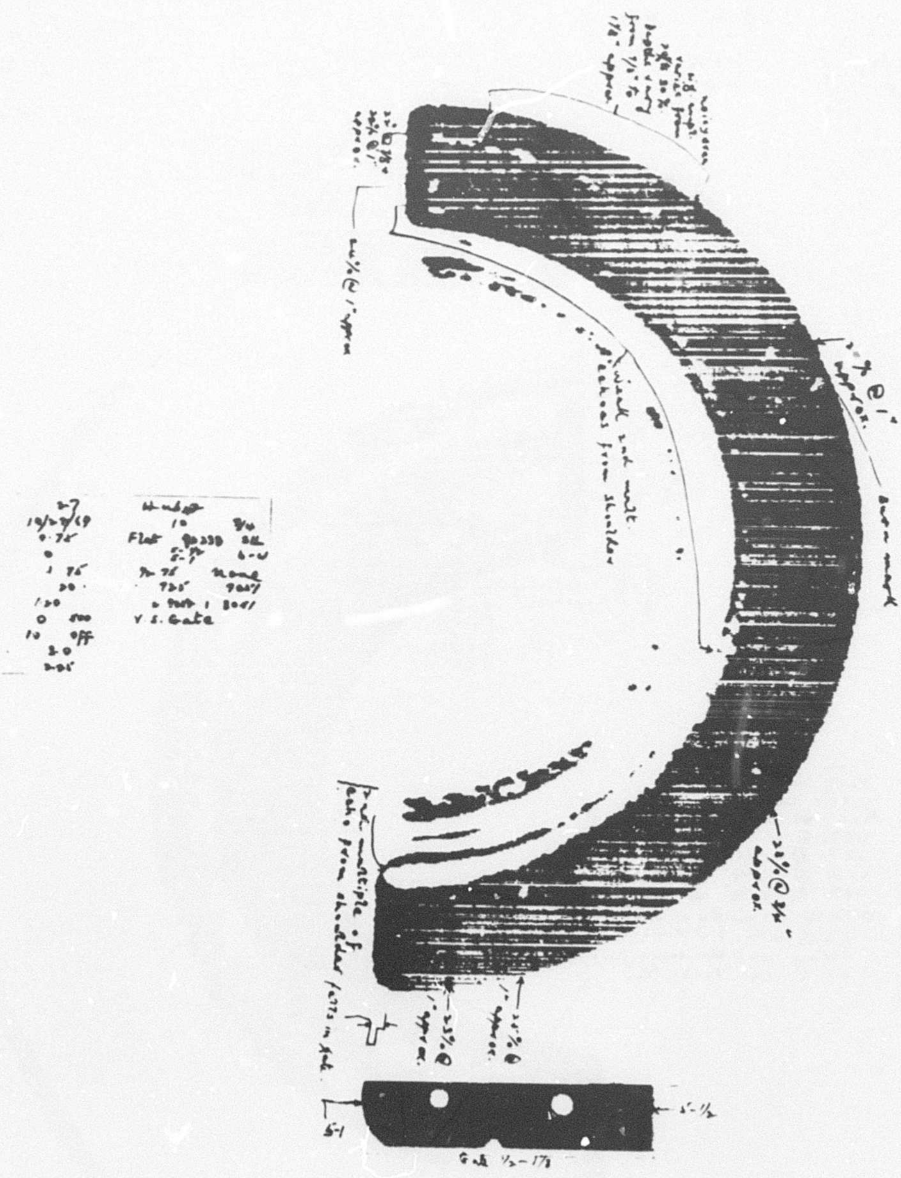
Gated on back surface
echo



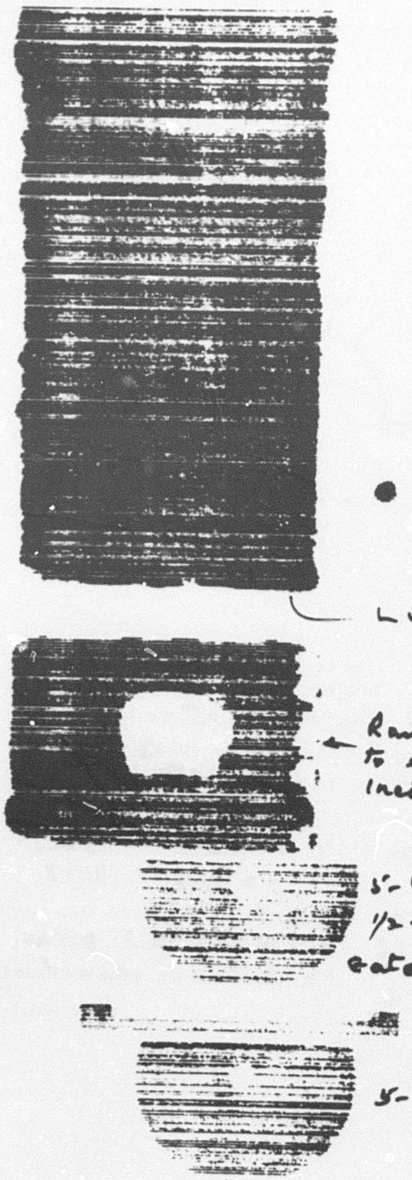
2.5	Hub #2		
10/21/69		10	3/4
0.55	Flat	9D 238	S/L
0		—	—
10-100		—	—
20		725	905%
1.0B		2 900S	1 805%
0 12.0	T.S. Gate		
10 off	Longer W.P. reqd. to keep 1st water multiple to		
3/2	the right of the back		
2.25	surface echo.		


Hub #2
10/21/69
Hub Center
Arms Down
5 - 1/2
Gate 1/2 - 6 1/2
5 - 5 3/4
Flange
Shoulder
2" down
approx.
20% ampl.
sigs. @ 3 5/8
+ 6 5/8" approx.
@ 28% ampl.
@ 1 5/8 + 30% ampl.
@ 5" approx.
@ 26% approx.
Very noisy
in this area *
Peaks as follows:
46% @ 4" approx.
50% @ 4 3/4 approx.
65% @ 4 5/8" approx.
48% @ 3 5/8" approx.
* Tried to make a setup for
3 3/4 & 4 3/4, but sensitivity
setting was the same for 3-4 3/4
as it was for 5-5 3/4.

Center Section Flange
Arms Down



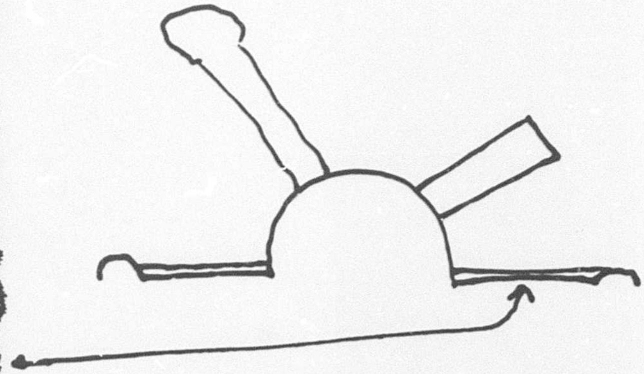
Arm Ramp
Arms Down



28	Huber	
10/30/69	15	3/4
2.1	Long 2613	S.L.
0	5-1/2 5-1	6-4
1 80	1/2 65	Name
20	325	7057
1.38	1 9013 1	8057
0 800	Ramp specimen with lambond used	
10 off	to set angle. Std.	
Varian	blocks to set sens.	
3.25		

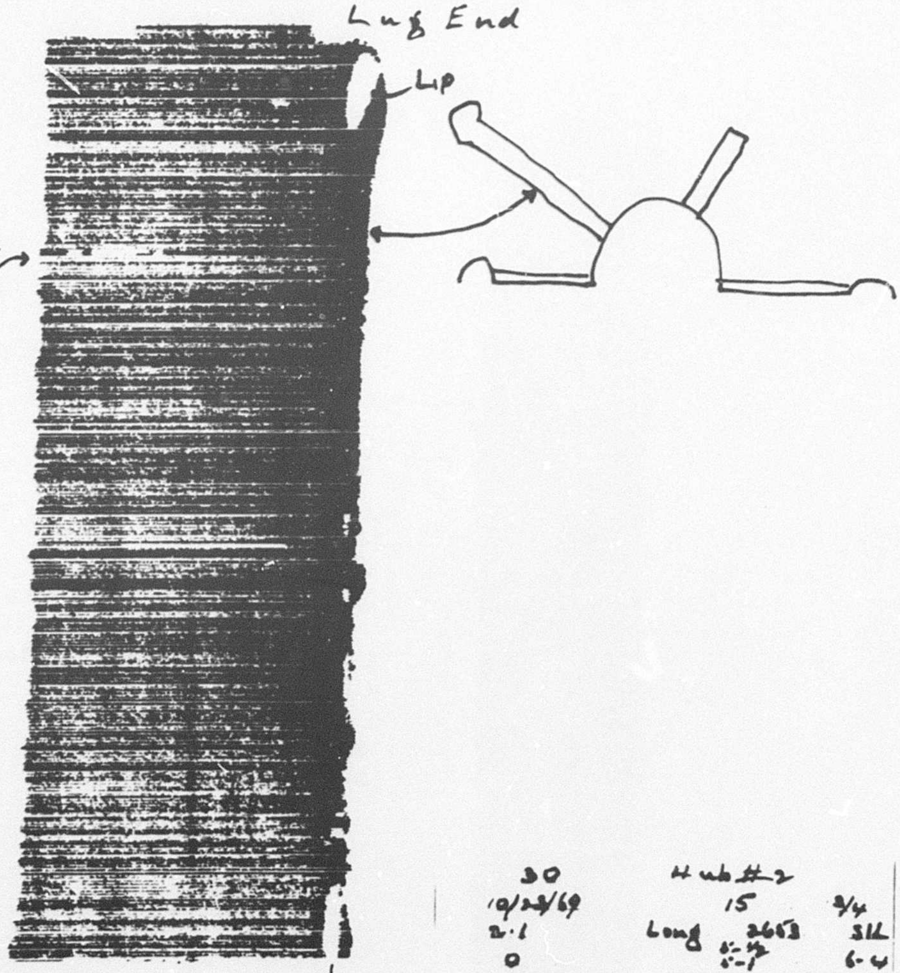
arm Ramp
arms Down

Lug end



RECORD NO 29 SPECIMEN Hub #2
DATE 10/22/69 SEARCH UNIT: FREQ 15 MHz. DIAM 3/4 IN
SENS. 211 FOCUS Long. S/N 2613. TYPE S/L
ATTEN. 0 DB STD. BLOCK: SIZE 5-1/2. MATL 6-4
SIGN. AMPL. 80% SIG. AMPL. 65%. [illegible] none
RECORD LEVEL 20% INSTRUM: TYPE 725. S/N 9081
DIAL 1.20 [illegible] ING FG 9042 [illegible] 8041
REJECT 0 PRF 500 V. S. Gate
DAMP 10 [illegible] off Lower PRF gives
WATER PATH Varing 2.25 IN "cleaner" recording

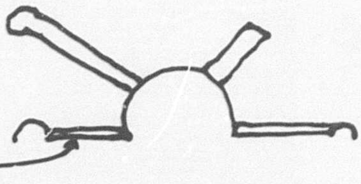
Arm Ramp
Arms Down



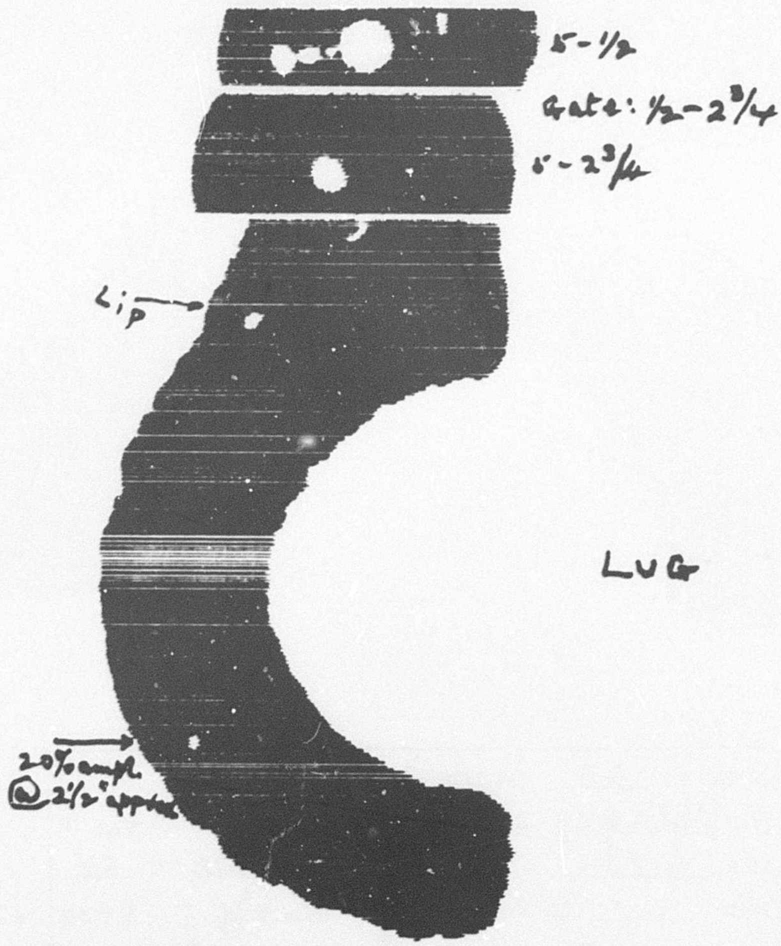
30	Hub #2		
10/28/69	15		3/4
2.1	Long	2653	SIL
0		8-½ 8-1	6-4
1 80	½ 65		none
20		72.5	7051
1.20		2 Pass 1	8051
2 600	V.S. Gate		
10 off			
Various			
3.25			

arm Ramp
Arms Down

Lug end



31	Hub #2	
10/23/69	1	3/4
2.1	Long 2653	81L
0	5-1/2 5-7	6-4
1 [illegible]	1/2 65	None
20	725	7051
1.20	2 9052 1	8081
0 590	V.S. Gate	
10 off		
WATER PATH Various		
3.25		



RECORD NO. 32 SPECIMEN H nb #2

DATE 10/23/69 SEARCH UNIT: FREQ 10 MHz. DIAM 3/4 IN

0.75 FOCUS Flat S/N 90230 TYPE SIL

ATTEN. 0 DB 5-1/2 5-2 3/4 MATL 6-4

42 75 2 3/4 max None

20 TYPE 725 7031

1.20 F2 9013 F1 8031

6 350 Y.S. Gate

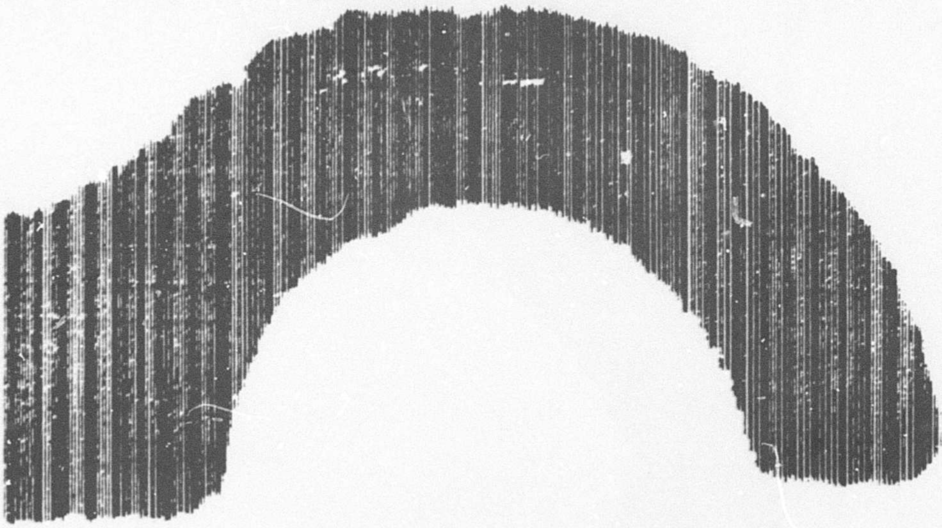
DAMP 10 off

WATER PATH 3.0 IN

2.25 MHz

NOT REPRODUCIBLE

Lug Arms Down



RECORD NO. 33 SPECIMEN Hub # 2

DATE 10/23/69 SEARCH UNIT: FREQ 10 MHz. DIAM 3/4 IN

SENS. 0.75' FOCUS Flat. S/N 90238 TYPE SIL

ATTEN. 0 DB STD. BLOCK: SIZE 5-1/2 5-2 3/4. MATL 6-4

SIGN. AMPL. 1/2 75% SIG. AMPL 3/4 100%. S/N None

RECORD LEVEL 80 % INSTRUM: TYPE 725 . S/N [illegible]

DIAL 1.20 PLUG INS FG 2 [illegible]. R [illegible]

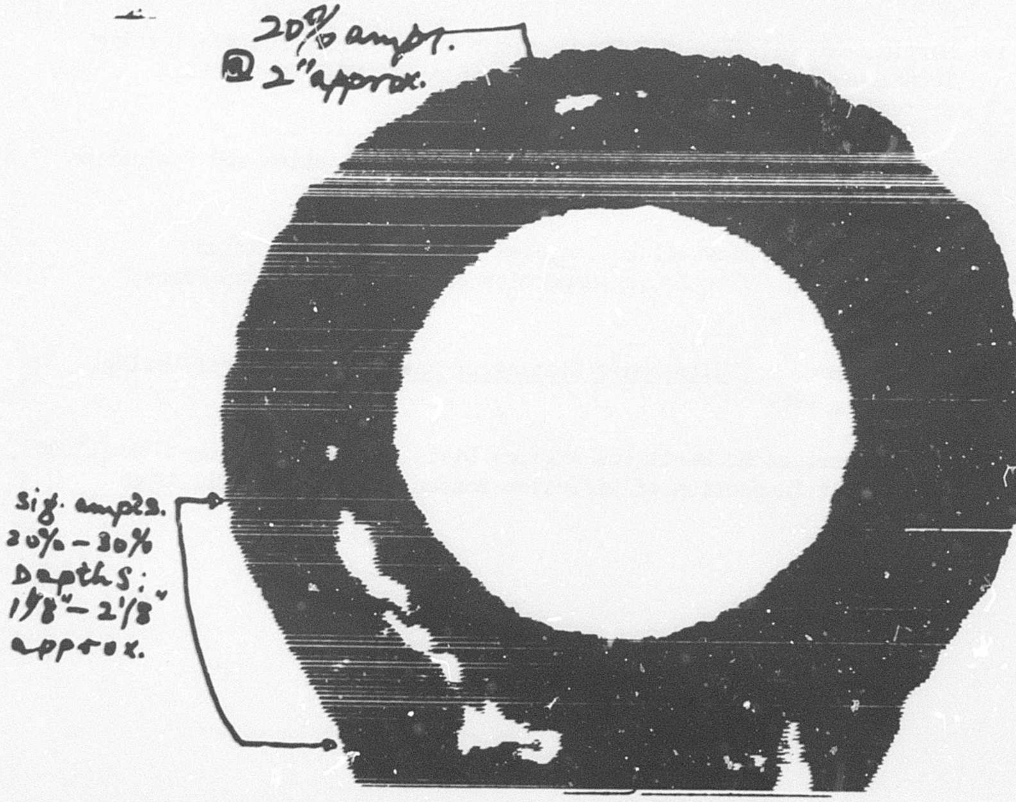
REJECT 0 PRF 800 [illegible] Y.S. Gate

DAMP 10 SWC off

WATER PATH 3.0 IN

[illegible] 2.25 [illegible]

LUG Arms Down



RECORD NO. 34 SPECIMEN Hub #2

DATE 10/23/69 SEARCH UNIT: FREQ 10 MHz. DIAM 3/4 IN

[illegible] 0.75 [illegible] Flat [illegible] 90238 TYPE SIL

ATTEN. 0 DB [illegible] 5–3/4 [illegible] MATL 6-4

[illegible] 75 % [illegible] 3/4 [illegible] None

[illegible] 20 % [illegible] TYPE 725 [illegible] 9051

DIAL 1.20 [illegible] 9013 [illegible] 8051

REJECT 0 [illegible] 500 V. S. Gate

DAMP 10 [illegible] off

WATER PATH 3.0 IN

[illegible] 3.25 [illegible]

NOT REPRODUCIBLE

REFERENCES

1. Martin, George, "Exploratory Development of Nondestructive Testing Techniques for Diffusion Bonded Interfaces," AFML-TR-68-253, September 1968

2. Contract AF33(615)-3515, Project 9122-1, "Fabrication and Evaluation of Diffusion Bonded Laminated Sections"

3. North American Rockwell Los Angeles Division Specification ST0501LT0003, "Ultrasonic Inspection of Diffusion-Bonded Parts," 1 December 1968

4. Krautkramer, J., Ultrasonic Testing of Materials, Springer-Verlag, New York, 1969

5. North American Rockwell Los Angeles Division Specification ST0501LT0002, "Penetrant Inspection of Diffusion-Bonded Parts," 14 April 1969

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
None	Air Force Materials Laboratory Wright-Patterson Air Force Base

13. ABSTRACT

The final technical report for a program investigating nondestructive testing (NDT) methods for diffusion bonded aerospace structures. The NDT methods evaluation was performed on three prototype H-53 helicopter rotor hubs diffusion bonded from 1/2-inch titanium plate under a concurrent contract. The NDT evaluation included ultrasonic, radiographic, and penetrant methods, and showed that ultrasonic techniques offered significant potential for developing a reliable, high sensitivity inspection system. Conventional ultrasonic techniques were the primary NDT method evaluated, and significant progress is reported in applying ultrasonic techniques to complex diffusion bonded structures. A most important factor is the need for systematic evaluation and understanding of the material effects on the acoustic beam propagation characteristics. Detailed recommendations are made for ultrasonic test improvements including data recording and analysis techniques; a unique ultrasonic "nodding" transducer system for inspecting discontinuities not normal to the inspection surfaces; a servo-controlled transducer manipulator system; an automatically controlled recorder gate system; and an automatic digital signal depth and amplitude measuring system.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Nondestructive Test						
Diffusion Bonding						
Ultrasonic						
Radiographic						
Penetrant						
Helicopter Rotor Hub						

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